Use of Multi-Attribute Utility Theory to Quantify the Desirability of Boiling Water Reactor Hydraulic Control Unit Maintenance Options

by

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Maria E. Silsdorf

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ABSTRACT

The role of maintenance in a nuclear power plant is to ensure that plant equipment is kept at a proper level of functionality, thus increasing the level of overall plant safety. In a deregulated electricity market, nuclear power plants must remain competitive with conventional utilities in the production of electricity. Consequently, nuclear utilities must find ways to improve their operations and reduce costs without sacrificing the level of overall plant safety and relationships with its stakeholders. One area of operations in which nuclear utilities can gain a competitive edge is in the maintenance of its power plants. By reducing the frequency of preventive maintenance and shifting the performance of selected maintenance items on-line, the utilities are able to reduce costs without significant impact to plant safety and relations to stakeholders.

This study focuses on the maintenance of hydraulic control units (HCUs) in Tokyo Electric Power Company's (TEPCO) boiling water reactors (BWRs). Using Multi-Attribute Utility Theory (MAUT), TEPCO decision makers can obtain a rank-ordering of multiple decision options based on their current preferences toward safety, cost, and stakeholder relations. In the case of HCU maintenance, the decision options considered are performance of HCU maintenance in the following conditions: 1) on-line with outage duration unchanged, 2) off-line with outage duration unchanged, 3) on-line with outage duration shortened, and 4) off-line with outage duration shortened. Because these options could have varying effects on safety, cost, and stakeholder relations, the use of MAUT facilitates decision making by providing a methodology that considers the effect of multiple factors simultaneously.

The literature search produced some useful information with regard to the maintenance practices of utilities from different countries, leading to a better understanding of maintenance philosophy, regulation, and routine in Japan. In addition, the search provided a wealth of information on the HCU maintenance practices of US utilities and the predominant failure modes observed in the system.

Through the use of performance indices, the desirability of each maintenance option can be quantified. The results of the study indicate that the best option is to perform on-line maintenance of the HCUs under the condition of a shorter outage. This option yielded the lowest overall performance index, indicating the lowest expected "disutility" among the other decision options.

Thesis Supervisor: Michael W. Golay
Title: Professor of Nuclear Engineering

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Introduction

1.1 General

The function of the hydraulic control units (HCUs) in boiling water reactors (BWRs) is to provide high pressure water for reactor scrams and to provide the hydraulic power necessary to move reactor control rods. By virtue of their importance to reactor safety, the HCUs are relied upon to perform their function 100% of the time. Needless to say, the tolerance for failure of the HCUs is very low and the maintenance requirements are stringent.

In the United States, most nuclear utilities perform preventive and corrective maintenance for the HCUs on-line (while the reactor is operating). This effort by US utilities to shift HCU maintenance on-line has resulted in shorter refueling outage durations, lower costs associated with refueling maintenance, a levelized workforce, and the ability to devote more resources to critical path items during refueling [1]. In Japan, all HCU maintenance is currently performed during refueling outages. Most work performed is preventive maintenance, and the problem this practice presents is that HCU maintenance performed off-line overburdens plant management, operators, and maintenance personnel. In addition, off-line HCU maintenance contributes greatly to the spike of employment during refueling outages, resulting in a maintenance work force that is not utilized during normal plant operation.

On-line HCU maintenance in the United States was accepted purely on deterministic analysis by plant utilities [2], with no explicit risk assessments being performed. Utility executives were convinced that on-line HCU maintenance was safe and beneficial because of the following reasons [3]:

1. All General Electric BWR HCUs are designed to be isolable, thereby easing the concern for industrial safety.

2. Off-line HCU maintenance was expensive, requiring the employment of contractors to perform the maintenance. On-line maintenance allowed the use of plant personnel for the performance of maintenance.

3. The impact to plant operations and replacement power cost was minimized by coordinating on-line maintenance with low power demand periods.

This study utilizes HCU maintenance as a case study for multi-attribute utility theory (MAUT) and how TEPCO can utilize MAUT in analyzing its decision options. Using this method, the favorability of the on-line and off-line HCU maintenance options are quantified.

1.2 Background

In an effort to enhance competitiveness in a deregulated electricity market, nuclear power plant producers must find ways to reduce costs while maintaining safety and stakeholder confidence. In Japan, Tokyo Electric Power's stakeholders are the Ministry of Economy, Trade, and Industry (METI) (governmental regulator), the local government, local workers, and the public. All decisions made must take into account the effect not only on safety and economics but also the effect on stakeholder relationships.

In recent years, there has been growing suspicion with nuclear power as the general public has witnessed the Tokai-mura criticality accident and as the media uncovered a scandal at the Monju fast breeder reactor. As a result of these incidents, the credibility of the nuclear industry in Japan has suffered, making the utility's decision-making process even more complicated as the stakeholders' acceptance of nuclear power wanes [4].

For optimal decision-making, the utility must take all of these factors into account. To satisfy many objectives (i.e. maintain safety to general public, maintain

good relations with stakeholders, and reduce expenses), the decision makers must carefully consider all consequences a specific decision could have. Because human beings are not consistent when making decisions involving multiple factors, a methodology is necessary to aid the decision maker in this task. In this study, MAUT provides a good analytical tool to determine which decision option is best.

1.3 Objective

The objective of the study is to rank the desirability of the following decision options for HCU maintenance, using MAUT:

1. On-line maintenance with no change in outage duration
2. Off-line maintenance with no change in outage duration
3. On-line maintenance with a shortened outage
4. Off-line maintenance with a shortened outage.

1.4 Method of Investigation

The first step in the development of a ranking of decision options for HCU maintenance was to gain a comprehensive understanding of the HCUs. We learned how the HCUs are constructed, their modes of operation, failure modes, and degradation mechanisms. Using this information, along with expert judgment provided by a visiting TEPCO engineer, we constructed fault trees for the failure events we determined to be most important in our analysis. These failure events (also known as Top Events) are as follows:

1. Excessive Scram Time
2. Failure to Scram
3. Inadvertent Control Rod Movement Inward
4. Inadvertent Control Rod Movement Outward
5. Failure to Move Control Rod Inward
6. Failure to Move Control Rod Outward.

Because HCU failure data from TEPCO was unavailable, we used data provided by the Institute of Nuclear Power Operations (INPO) from the Nuclear Plant Reliability Data System (NPRDS) database to determine probabilities for each top event.

Figure 1.1 shows the overall methodological structure for characterizing TEPCO's decision making values developed by Koser, Sato, et al [4]. It consists of the value tree, the utility analysis, and the decision options. The value tree is a hierarchical representation of the objectives that support the decision-making process [5] and is a reflection of what factors the decision maker must consider when weighing various decision options. The utility analysis consists of an examination of the effect of each decision option on the performance measures represented in Tier 5 of Figure 1.1. Finally, the decision options for this case study are listed in Section 1.3.

In order to rank the favorability of each decision option, we used MAUT to provide a quantity called the Performance Index (PI), known in standard MAUT textbooks as the "Expected Utility." The PI is calculated for each decision option and the option with the lowest PI is the most favorable one.

1.5 Terminology

The following terms are used in this study:

1. Critical Path: The sequence of operations that must be performed serially during a refueling outage. Items on critical path, if not completed, will prevent the plant from returning to full operational status.
2. On-line maintenance: Maintenance that is performed while the plant is operating.
3. Off-line maintenance: Maintenance that is performed while the plant is shutdown, typically during refueling outages.
4. Technical Specifications: Specifications that define limits and conditions to assure nuclear power plants are operated in a manner consistent with the analyses and evaluations in the plant's Safety Analysis Report. [6]

5. Corrective Maintenance: The actions needed to restore the operability of failed or degraded equipment within acceptable limits. These actions include repairs or replacement for failed equipment and maintenance actions for those degradations where immediate corrective actions are preferred. [6]

6. Preventive Maintenance: The actions that detect, preclude, or mitigate degradation of a functional component to sustain or extend its useful life by controlling degradation and failures at an acceptable level. [6]

7. Scram: The rapid emergency shutdown of a nuclear reactor by rapid insertion of all control rods.

8. Nuclear Plant Reliability Data System (NPRDS): A computer-based collection of engineering, operational, and failure data on systems and components installed in U.S. nuclear plants. The NPRDS can help improve plant equipment performance in a number of ways, including the following: [7]

- Identifying high-failure-rate equipment,
- Identifying plants that have a particular equipment problem,
- Identifying plants with possible spare parts and equipment that could be made available to other plants,
- Selecting vendors and equipment for plant modifications based on component reliability,
- Optimizing spare parts inventory based on failure rates and replacement history,
- Scheduling and defining preventive and predictive maintenance activities,
- Providing input to plant availability studies,
- Providing data for reliability-centered maintenance programs.

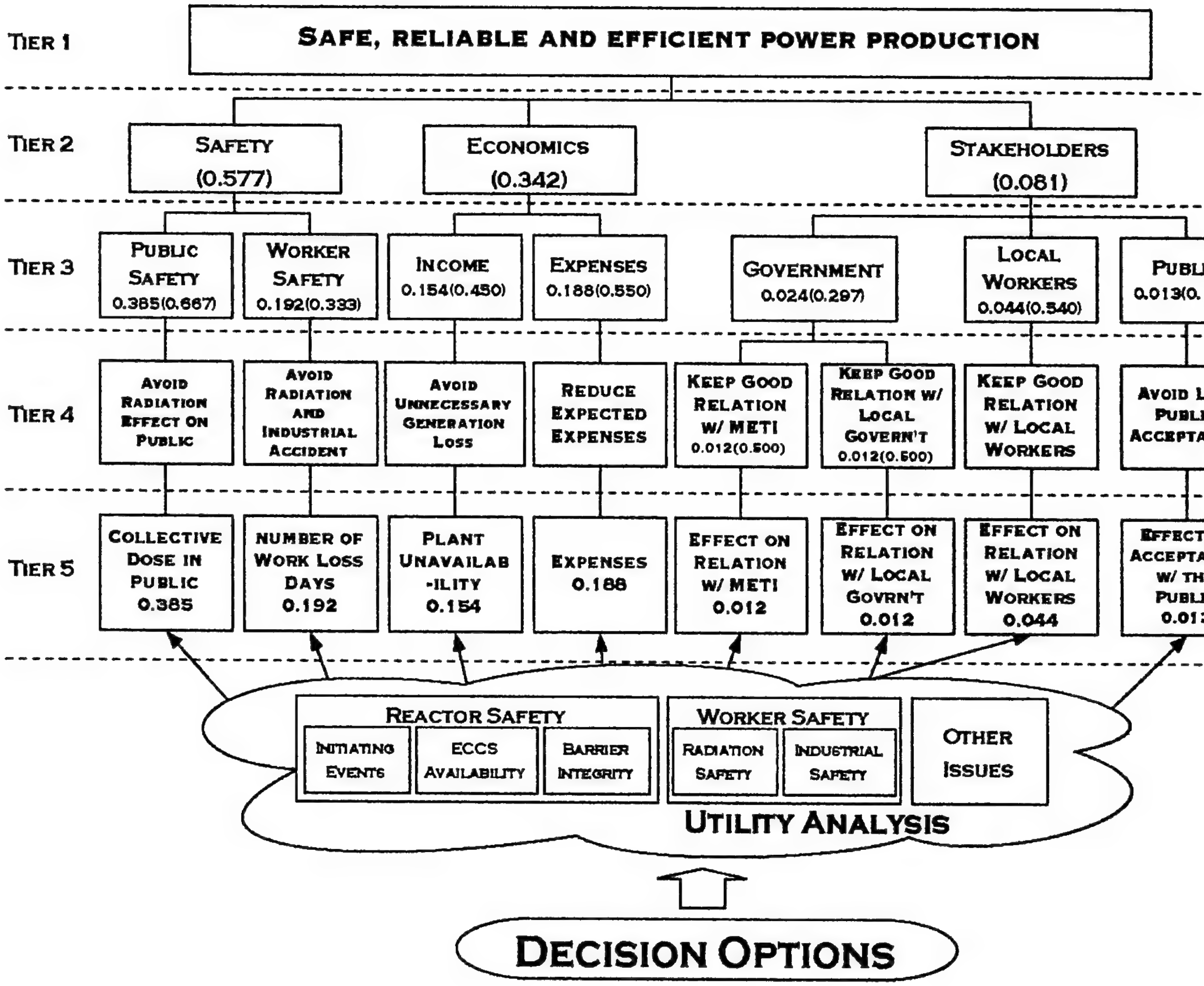


Figure 1.1—Overall Methodological Structure for Characterizing TEPCO's Decision Making Values [4]

Literature Search

2.1 General

This section summarizes the literature search performed to gain familiarity with the maintenance practices of Japan and how they differ in comparison to maintenance practices of the US.

2.2 Overview of Japanese Nuclear Industry Maintenance Practices

2.2.1 Industry Description

Nuclear power currently supplies approximately 36% of the power consumed in Japan—it ranks 3rd in the world in total capacity. There are 51 operating plants (23 PWRs and 28 BWRs) [8] and because of Japan's limited resources, nuclear power promises to play an even bigger role in the future as the country seeks independence from foreign sources of fuel. [9] The Japanese public places a great deal of emphasis on safety in the nuclear industry and on minimizing radiation exposure to workers and to the public.

2.2.2 Regulatory Structure

The Japanese Fundamental Act of 1955 delegated responsibility for regulation of commercial nuclear reactors to the Ministry of Economy, Trade and Industry (METI). Once known as the Ministry of International Trade and Industry (MITI), it traces its regulatory jurisdiction of maintenance at commercial nuclear power plants to the Electric Utility Industry Law and the Law for the Regulation of Nuclear Source Materials, Fuel Materials, and Reactors. [10]

The Electric Industry Law sets forth the technical standards for the installation, operation, and maintenance of electrical structures; in addition, this law also mandates the periodic inspection which occurs during scheduled outages for inspection and maintenance.

2.2.3 Maintenance Practices and Regulations

Japan's structured, industry-wide program of preventive maintenance consists of four basic elements: 1) statutory annual inspection, 2) voluntary internal inspection, 3) special work, including backfitting and corrective maintenance, and 4) routine inspection. The first three are conducted during the annual inspection (required at least every 13 months) and the last is conducted during routine plant operation. [10]

During the outage, approximately 70 items in the plant are disassembled and inspected. Although the duration of outages is decreasing because of more efficient inspection procedures [11], technical improvements in maintenance and repair, and extensive education and training programs, the average outage duration in Japan is 90 days [12]. In the United States, outages are as short as 20 days.

Preventive maintenance on plant components is also performed during outages, and the Japanese preventive maintenance program is so effective that plants are seldom required to shut down during plant operation to fix problems.

2.3 Comparison of US and Japanese Maintenance Practices

2.3.1 Technical Specifications

In the United States, technical specifications delineate preventive maintenance requirements that are largely operational in nature, meaning that they are comprised of functional tests and verification of operation that are mostly performed during normal operation. In contrast, the Japanese perform extensive inspections that require complete

disassembly of components. Most of the mechanical inspections and functional tests are performed during the inspection outages. Technical specifications in the United States are largely limited to safety related systems and components; however, the Japanese also include non-safety related equipment such as condenser systems, feedwater systems, and turbine generator auxiliaries. In general, the numbers and types of components subject to inspection are much greater than current technical specification requirements in the US.

2.3.2 Regulator Oversight

In Japan, METI involves itself in the preventive maintenance program by witnessing a significant number of maintenance activities during annual plant outages. There is no requirement in the US for the Nuclear Regulatory Commission to witness maintenance activities.

2.3.3 Summary

Japanese reactors experience significantly fewer trips than US reactors not because of differences in trip setpoints or technical specifications, but due to the structured, industry-wide program of extensive preventive maintenance. This program consists of statutory annual inspections, voluntary internal inspections, special work, and routine inspections. In addition, the Japanese regulatory authority, METI, is heavily involved in the maintenance process and witnesses most maintenance activities during each annual outage.

General Electric BWR Hydraulic Control Unit System

3.1 Introduction

This section is devoted to familiarizing the reader with the HCU system, its function and operation, degradation mechanisms, and failure modes. In addition, the current HCU maintenance practices of Japan and the United States will be compared and technical specifications discussed.

3.2. General Description

The HCU consists of all the hydraulic, electrical, and pneumatic equipment necessary to move one control rod drive mechanism (CRDM) during normal and scram operation. All TEPCO BWR/5s have 185 HCUs (The BWR/4 and BWR/6 have 137 and 193 HCUs, respectively). Figure 3.1 shows the general construction of the HCUs.

3.3 Function

The HCU performs the following three specific functions: [13]

1. Provides high pressure water from the accumulators to enable the control rod assemblies to scram. One HCU provides scram power for one CRDM.

2. Contains the valve configuration for normal CRDM movement inward or outward using solenoid-operated and directional control valves.

3. Provides cooling water flow path to the CRDM.

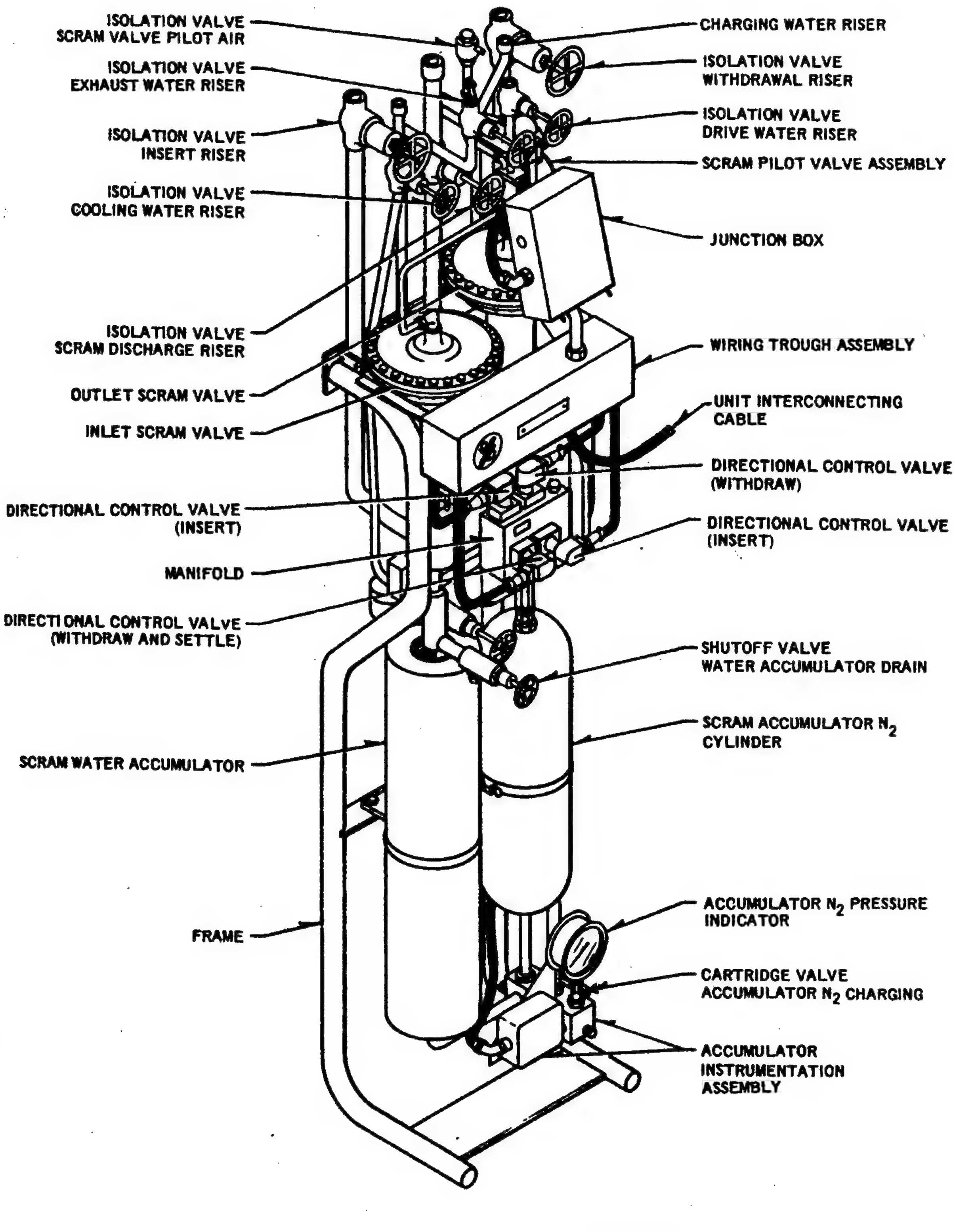


Figure 2-13. Control Rod Drive Hydraulic Control Unit

Figure 3.1—Control Rod Drive Hydraulic Control Unit [13]

3.4 Main Components

The main components of the HCU system are as follows:

1. *Directional Control Valves*: (Valves 120, 121, 122, 123) These valves direct drive and exhaust water for control rod movement. The rod control and information system provides proper sequencing and duration of the signals used to operate these valves.

2. *Scram Inlet and Outlet Valves*: (Valves 126 and 127, respectively) Normally held shut by instrument air pressure applied to their actuators, these valves control water flow for the scram function.

3. *Scram Solenoid Pilot Valves*: These valves control the air that is supplied to the scram valves. The scram solenoid valves are normally energized to maintain instrument air pressure that keeps the scram valves shut. When a scram signal is received, the solenoids deenergize, venting instrument air, and allowing the scram valves to open by spring action.

4. *Scram accumulators*: The scram accumulator is a piston water accumulator that is pressurized by a volume of nitrogen gas in a nitrogen cylinder. The piston in the scram accumulator forms a barrier between the high-pressure nitrogen gas used as the source of stored energy and the water used to initiate a scram. Under normal plant operating conditions the piston is in full down position. The control rod drive hydraulic pump continuously pressurizes the scram accumulators through the charging water header. Figure 3.2 illustrates the components discussed above.

3.5 Operation

3.5.1 CRDM Scram Operation

When a reactor scram is initiated by the reactor protection system, the control air is vented from the scram valves through the deenergization of relays associated with the scram solenoid pilot valves (SSPVs). As the air is vented, the inlet and outlet scram

valves open by spring action. Opening the scram outlet valve reduces the pressure above the main drive piston of the CRDM to atmospheric pressure while opening the scram inlet valves allows high pressure water (~1800 psi) from the accumulator to the bottom of the piston. Figure 3.3 depicts this action.

3.5.2. CRDM Insert Operation

The insert operation is accomplished by opening directional control valves 121 and 123, as shown in Figure 3.4 When these valves open, water from the drive water header applies drive water pressure to the bottom of the control rod drive piston. At the same time, water above the piston will flow to the exhaust header. The differential pressure created across the drive piston forces the control rod into the core.

3.5.3 CRDM Withdraw Operation

"The weight of the control rod blade and the index tube/drive piston assembly is approximately 125N (280 lb) and the tops of the notches on the index tube are square. Therefore, the friction between the index tube notch and the collet fingers is too great to allow a pressure force from the collet piston to remove the fingers from the square notches. So, initially, an insertion signal is applied for a short time (0.5s), which causes the rod to insert. As the rod inserts, the collet fingers slide out over the tapered bottom of the notch in the index tube." [14]

Following a brief insert signal that allows the rod to disengage from the collett fingers, a withdraw signal opens directional control valves 120 and 122 as shown in Figure 3.5. Drive water pressure is applied to the area above the drive piston while the volume below the drive piston is discharged to the exhaust header. The differential pressure created forces the rod out of the core.

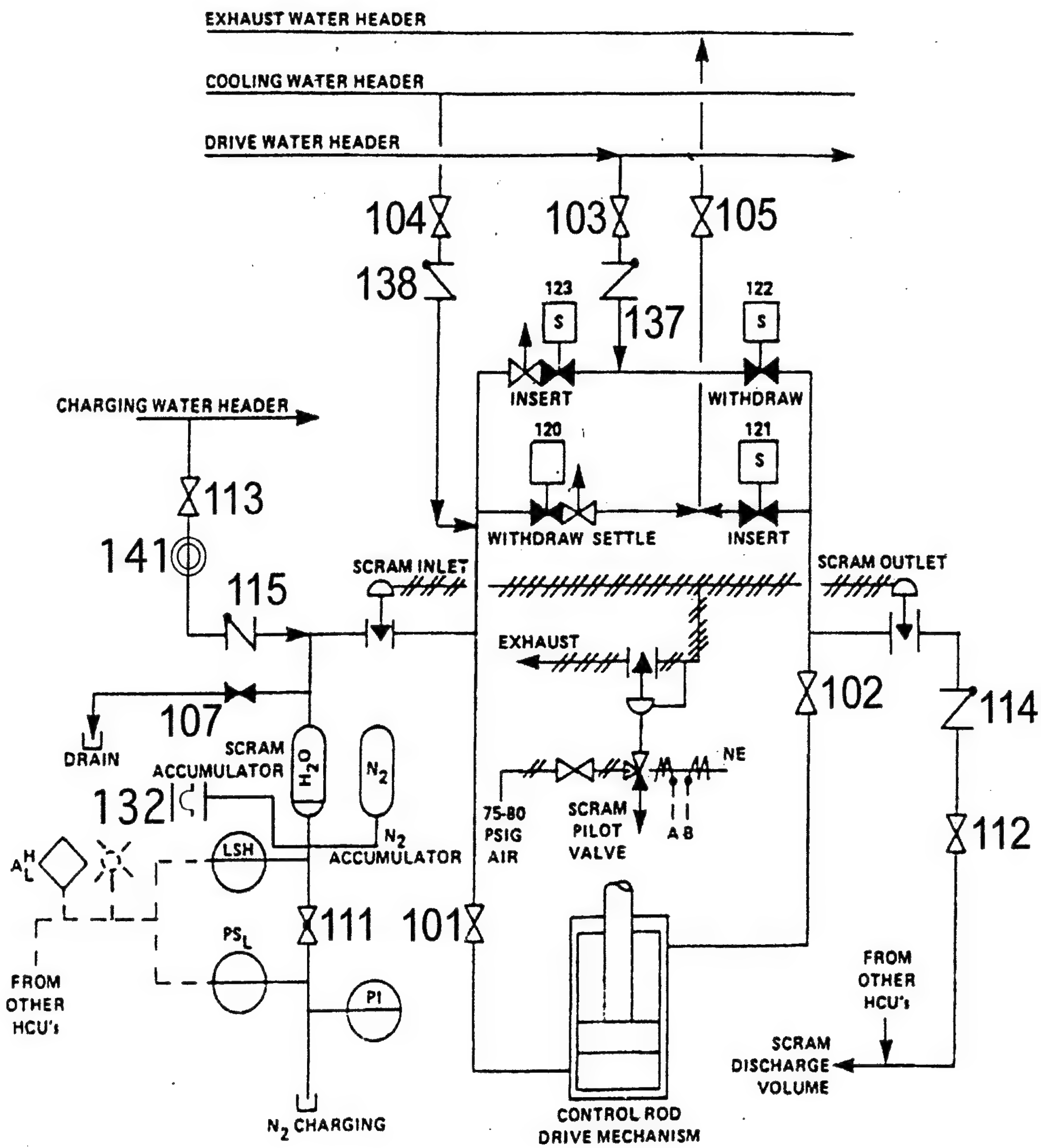


Figure 3.2 Control Rod Drive Hydraulic System Schematic Diagram [15]

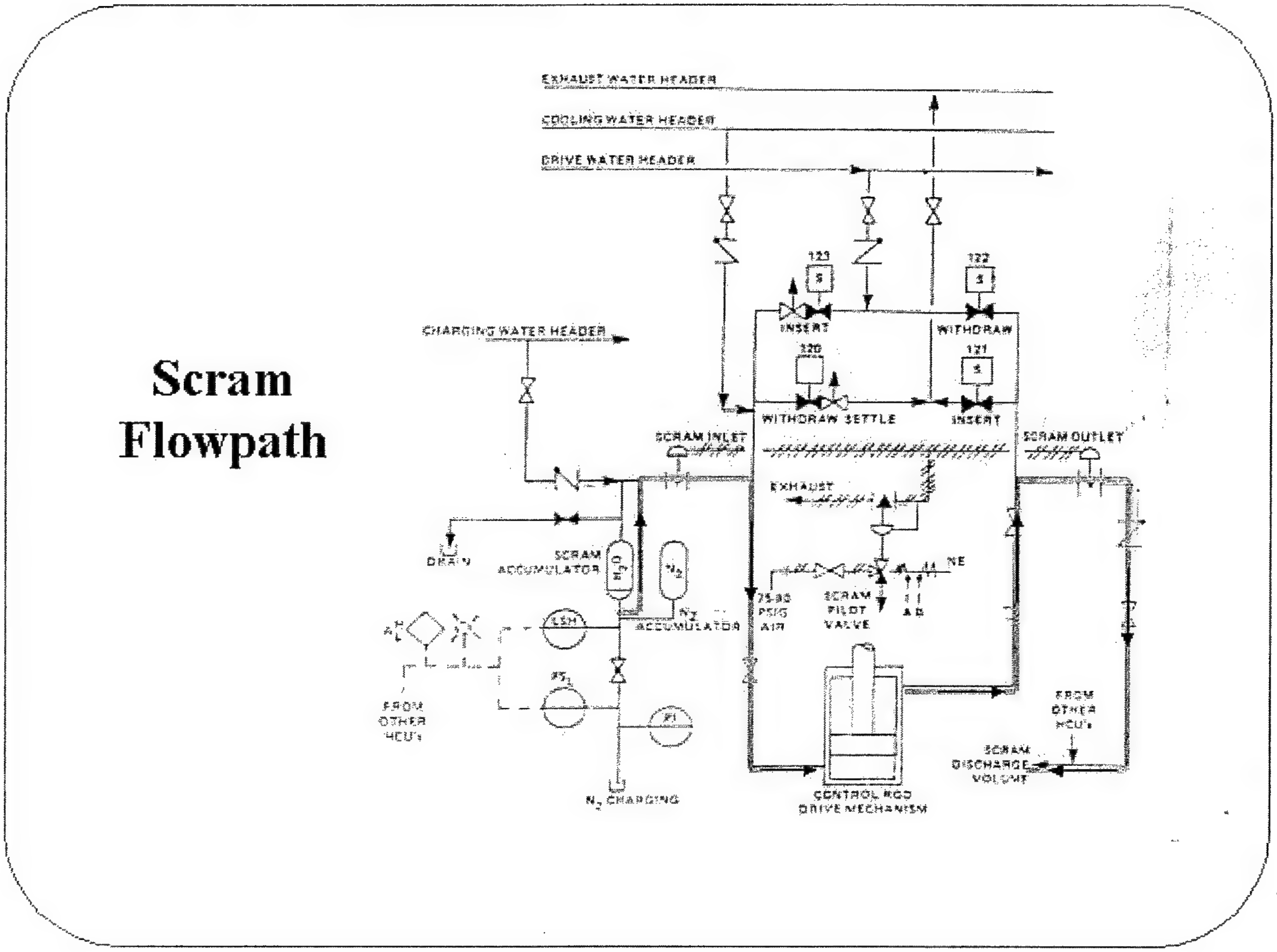


Figure 3.3 Scram Operation Flowpath [16]

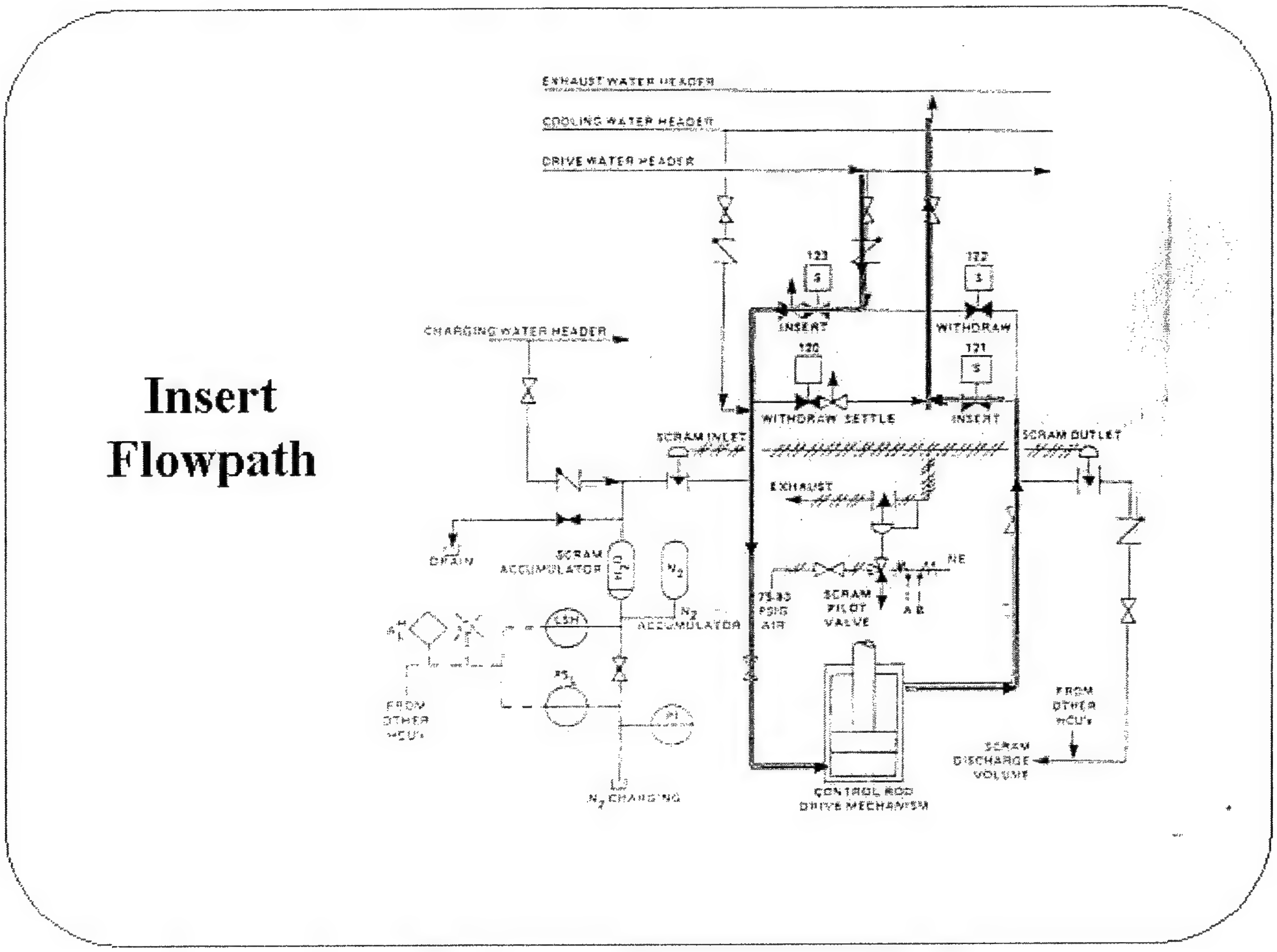


Figure 3.4 Insert Operation Flowpath [16]

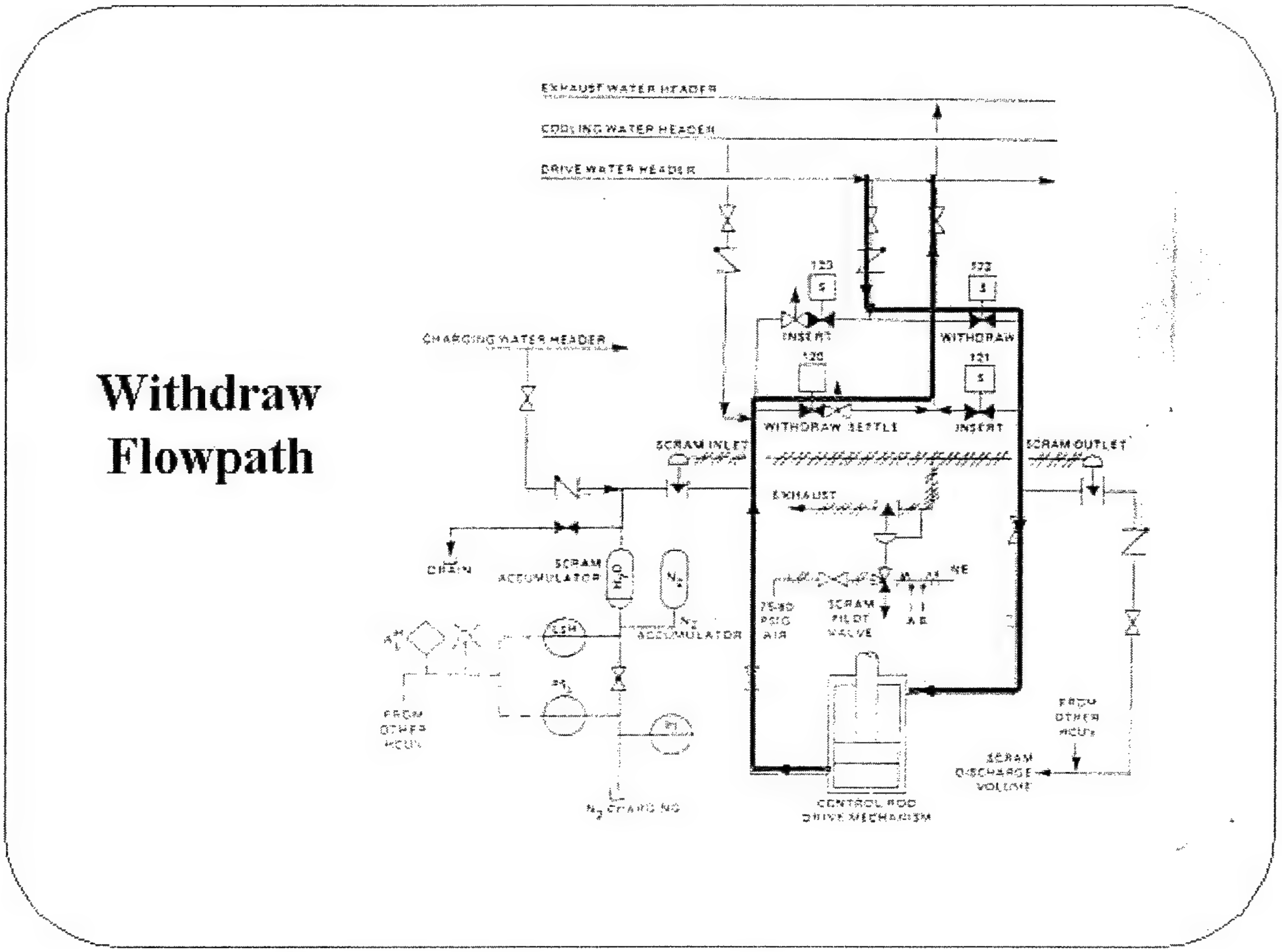


Figure 3.5 Withdraw Operation Flowpath [16]

3.6 HCU Component Failures and Degradation Mechanisms

Based on a Nuclear Plant Aging Research (NPAR) study that examined the aging processes associated with BWR CRDMs, it was discovered that the HCU contributed the majority of failures associated with the control rod drive system. More than 59% of the 3432 CRD system failures reported to the NPRDS were attributed to failures to HCU components [15]. The following is a list of predominant HCU components failures:

1. *Accumulator Nitrogen Charging Cartridge Valve*: (Valve #111) Leading reported causes of failure were worn valve packing, normal valve wear and aging, and worn valve stem.

2. *Scram Discharge Riser Isolation Valve*: Intergranular Stress Corrosion Cracking was blamed for the failures of these valves as the valve wedge separated from the stem.

3. *Scram water accumulator*: The chromium plating of the carbon steel tank was porous enough to allow water to seep into the carbon steel and cause corrosion, resulting in blistering and pitting of the plating throughout the cylinder. These loose flakes would leave the accumulator and collect on the Teflon seat of the inlet scram valve, causing some leakage. GE and Toshiba developed a stainless steel replacement for this unit.

4. *Inlet and Outlet Scram Valves*: Primary causes of degradation were aging of the valve seat, multiple valve parts aging, worn valve packing, and worn valve diaphragms.

5. *Scram Solenoid Pilot Valves*: The causes of failure most frequently observed were worn diaphragm, aged solenoid components (such as coil "short" or blown fuse), and normal valve wear or aging. Also observed was degradation of the valve seats, caused by cracking on the Buna-N rubber discs. This cracking was accelerated by long-term exposure to head from the solenoid coil and by oil and water contaminants in the instrument air supply. The symptoms of scram pilot valve and solenoid degradation include slow scram times, leaking air, and abnormal solenoid noise. [17]

3.7 Maintenance-Related Failures

From a review of 2500 NPRDS HCU system failure reports, it was found that approximately 120 were directly attributed to previous maintenance or human error during maintenance. The NPRDS data reviewed spanned from 1978-1996. Major contributors to maintenance-related failures include the following:

1. Improper installation of parts
2. Improper adjustment of parts
3. Contamination introduction during maintenance.

3.8 Current HCU Maintenance Practices

The maintenance practices of the United States and Japan are starkly different with regard to the HCUs. Whereas the majority of US plants have converted to performing HCU maintenance on-line, the Japanese perform their HCU maintenance off-line, during annual outages.

3.8.1 Japanese HCU Maintenance Practices

As mentioned earlier, the Japanese perform all preventive and corrective maintenance on the HCUs during every annual outage. Although HCU work is non-critical path, any delay in HCU work will adversely affect the progress of CRDM work, which is critical path. During a given outage, a minimum of 20 HCUs are maintained by contractor personnel. The maintenance involves complete disassembly of components, replacement of parts, METI inspection, reassembly, leak tests, and operational tests. Table 3.1 is a listing of a few examples of HCU preventive maintenance requirements and their periodicities. [18]

MAINTENANCE ACTION	PERIODICITY
Replace diaphragm of scram valve actuators	5 years
Clean up of bodies, bonnets, stems and valve seats of selector valves followed by CRD tuning and leak/functional checks Clean up of rupture disks	5 years
Clean up accumulators and nitrogen volumes	7 years
Clean up bodies, bonnets, stems, valve seats of scram valves and manually operating valves	10 years

Table 3.1—Japanese HCU preventive maintenance requirements

3.8.2 US HCU Maintenance Practices

In the United States, most nuclear utilities perform HCU maintenance during normal plant operation. For plants with scheduled outage durations of approximately 20 days, on-line HCU maintenance is necessary because critical path items require the involvement of all plant personnel [1], leaving little or no resources for other work. By switching to on-line maintenance, including that of HCUs, US plants have 1) managed to shorten plant outage durations, 2) lowered costs associated with refueling maintenance, 3) allowed more resources to be devoted to critical path items during refueling, and 4) employed more in-house plant personnel in the performance of HCU maintenance.

Unlike the Japanese, US utilities do not have a structured and standard policy for HCU maintenance. The Japanese have industry-wide preventive maintenance requirements for HCUs during every outage, while the US plants each differ in their approach. What is performed during HCU on-line maintenance is decided individually by each plant, with some plants emphasizing preventive maintenance and others focusing on corrective maintenance. In other words, the overwhelming practice in the US is to replace HCU components as they fail [1], rather than having a strict preventive maintenance schedule to follow. However, for components that are prone to failure, some utilities have adopted preventive maintenance requirements. Examples of these components include the scram solenoid pilot valves (most utilities change out components every 15 years) and scram valves diaphragms (changed out every 15 years at most plants). [1]

On-line HCU maintenance was accepted in the US because it was viewed as a practice where the benefits would be great while the risks were low. The main goal was to reduce the cost of work performed during outages, and on-line HCU maintenance achieved this by reducing the outage duration and breaking the utilities' reliance on contractor personnel to perform maintenance. The arguments that convinced utility executives that on-line HCU maintenance would be safe and beneficial were the following: [3]

1. All General Electric BWR HCUs are designed to be individually isolable, allowing maintenance to be performed in a safe condition, thereby easing the concern for maintaining industrial safety.
2. Off-line HCU maintenance was costly because contractor personnel were relied upon to perform the maintenance. On-line maintenance allows trained in-house personnel to perform HCU maintenance during normal power operation.
3. The effect upon the plant and the cost of replacement power could be reduced by coordinating necessary electric load drops with low power demand periods.

As for the NRC, on-line maintenance was judged to be acceptable if the utilities remained within their respective Technical Specifications [1]. The Technical Specifications for control rod operability are given in Table 3.2. The US utilities are able to perform HCU maintenance on-line because the technical specifications allow one or more control rods to be inoperable if 1) the rod is fully inserted within 3 hours and 2) disarmed within four hours (see Condition C in Table 3.2).

3.1 REACTIVITY CONTROL SYSTEMS

3.1.3 Control Rod OPERABILITY

LCO 3.1.3 Each control rod shall be OPERABLE.

APPLICABILITY: MODES 1 and 2.

ACTIONS

- NOTE -
Separate Condition entry is allowed for each control rod.

CONDITION	REQUIRED ACTION		COMPLETION TIME
A. One withdrawn control rod stuck.		- NOTE - Rod worth minimizer (RWM) may be bypassed as allowed by LCO 3.3.2.1, "Control Rod Block Instrumentation," if required, to allow continued operation.	
	A.1	Verify stuck control rod separation criteria are met.	Immediately
	AND		
	A.2	Disarm the associated control rod drive (CRD).	2 hours
	AND		

Table 3.2 Control Rod Operability Technical Specifications [19]

CONDITION	REQUIRED ACTION		COMPLETION TIME
	A.3	Perform SR 3.1.3.2 and SR 3.1.3.3 for each withdrawn OPERABLE control rod.	24 hours from discovery of Condition A concurrent with THERMAL POWER greater than the low power setpoint (LPSP) of the RWM
	<u>AND</u>		
	A.4	Perform SR 3.1.1.1.	72 hours
B. Two or more withdrawn control rods stuck.	B.1	Be in MODE 3.	12 hours
C. One or more control rods inoperable for reasons other than Condition A or B.	C.1	**- NOTE -** RWM may be bypassed as allowed by LCO 3.3.2.1, if required, to allow insertion of inoperable control rod and continued operation. Fully insert inoperable control rod.	3 hours
	<u>AND</u>		
	C.2	Disarm the associated CRD.	4 hours

Table 3.2 Control Rod Operability Technical Specifications [19]

CONDITION	REQUIRED ACTION		COMPLETION TIME
D. ------------------------- **- NOTE -** Not applicable when THERMAL POWER > [10]% RTP. ------------------------- Two or more inoperable control rods not in compliance with banked position withdrawal sequence (BPWS) and not separated by two or more OPERABLE control rods.	D.1	Restore compliance with BPWS.	4 hours
	<u>OR</u>		
	D.2	Restore control rod to OPERABLE status.	4 hours
E. ------------------------- **- NOTE -** [Not applicable when THERMAL POWER > [10]% RTP. ------------------------- One or more groups with four or more inoperable control rods.	E.1	Restore control rod to OPERABLE status.	4 hours]
F. Required Action and associated Completion Time of Condition A, C, D, or E not met. <u>OR</u> Nine or more control rods inoperable.	F.1	Be in MODE 3.	12 hours

Table 3.2 Control Rod Operability Technical Specifications [19]

Fault Tree Analysis

4.1 Introduction

In order to analyze complex systems and their modes of failure of components and actions, it is necessary to construct fault trees. A fault tree shows the logic connecting individual failures (basic events) to system failures (top events), and it also allows the calculation of system failure probability (top event probability) using Boolean algebra. In this study, the fault tree was utilized to calculate the probabilities for the following top events in the HCU system:

Top Event 1: Excessive Scram Time
Top Event 2: Failure to Scram
Top Event 3: Inadvertent Rod Motion Inward
Top Event 4: Inadvertent Rod Motion Outward
Top Event 5: Failure to Move Control Rod Inward
Top Event 6: Failure to Move Control Rod Outward.

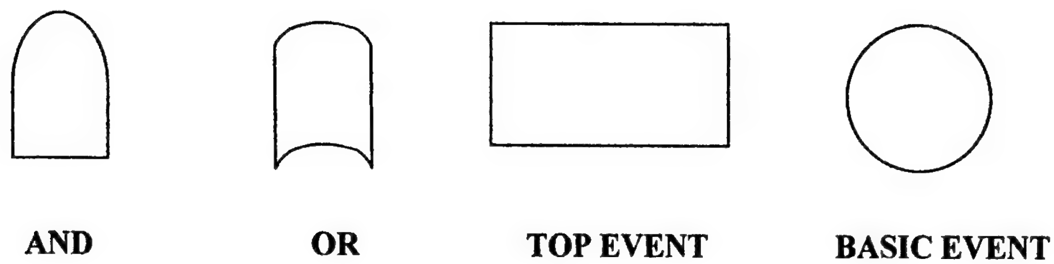
4.2 Definition of Top Events

The top events are as follows:

1. Excessive Scram Time: Time to scram rod exceeds time specified in technical specifications.
2. Failure to Scram: Control rod fails to insert when scram signal is received.
3. Inadvertent Rod Motion Inward: Control rod moves inward without application of scram signal or inward motion signal from reactor instrumentation and control.
4. Inadvertent Rod Motion Outward: Control rod moves outward without application of outward motion signal from reactor instrumentation and control
5. Failure to Move Control Rod Inward/Outward: Failure to control rod to respond to inward/outward signal from reactor instrumentation and control.

4.3 Symbols of Fault Tree Analysis

Figure 4.1 summarizes the conventional fault tree symbols.



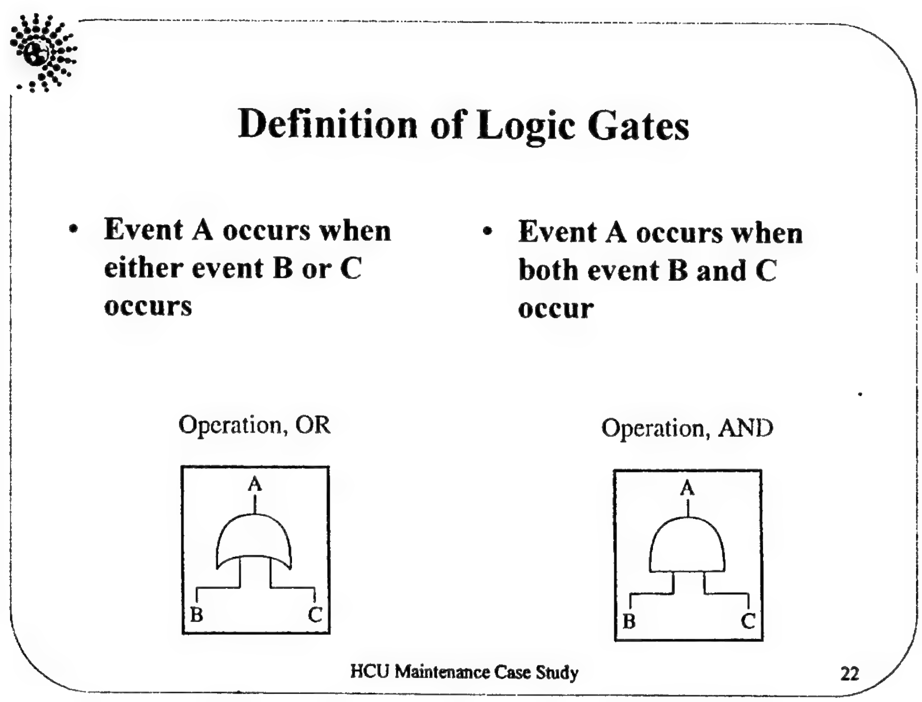


Figure 4.1 Conventional Fault Tree Symbols

4.4 Example of Fault Tree Analysis

To illustrate how a simple fault tree analysis is structured, the internal combustion engine shown in Figure 4.2 is considered. Figure 4.3 is the fault tree constructed that diagrams how the top event "Low cylinder compression" (LCC) may occur. Using the "+" for the "OR" operation and "X" for the "AND" operation, the following Boolean equation is acquired for the top event:

$$\mathbf{LCC = HG + IV + SP + (PR1 * PR2)}$$

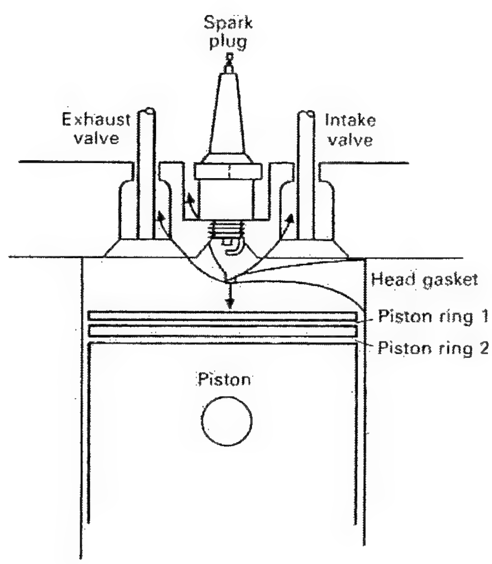


Figure 4.2 Internal Combustion Engine [20]

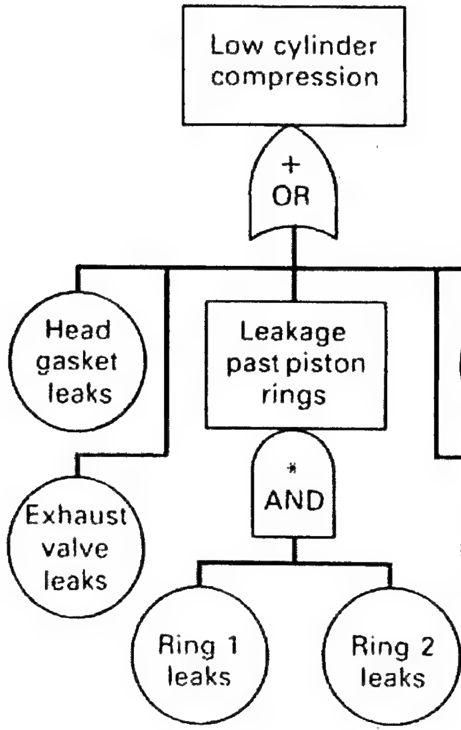


Figure 4.3 Fault Tree for Low Cylinder Compression ; LCC = HG + IV + SP + (PR1 * PR2) [20]

4.5 Determination of Basic Event Probabilities

In the determination of the values of the top event probabilities for the HCU, basic event data were acquired primarily from the INPO database of NPRDS failure reports. The database spanned the interval from 1978-1996 and contained approximately 3500 failure reports of the HCUs of US utilities. For this study, we analyzed data from four nuclear power plants: Brunswick 1, Peach Bottom 3, Quad Cities 1, and Susquehanna 1.

The determination of basic event frequencies was performed by utilizing the following equation:

$$\textbf{Basic event frequency} = \frac{\textbf{Number of basic event occurrences}}{\textbf{(Number of components available) * (Report Interval)}}.$$

Unfortunately, not all of the basic events in the fault trees were accounted for in the NPRDS database, requiring educated guesses to be made about their probability values. This was done by selecting similar basic events for which data were available and assigning their frequencies of occurrence to the basic events for which data were not available. For example, there were no explicit data available for the basic event "SSPV failure to vent due to improper substances used during maintenance", but there were data available for the basic event "SSPV failure to vent due to debris intrusion." The number of occurrences for the latter event was also assumed to obtain the former, resulting in a guess at the "SSPV failure to vent due to improper substances used during maintenance" basic event probability.

Finally, for those events where data were not available and there existed similar events for which actual occurrences had been observed, we assigned one occurrence during the report period. Appendix A contains fault trees for Top Events 1 through 5 and all basic event probability and top event probability data.

4.6 Treatment of Human Error

When data are not available for basic events which are directly attributable to human error, we must estimate the values of their respective Human Error Probabilities (HEP). In this study, we utilized the Technique for Human Error Rate Prediction (THERP) to estimate the HEP values related to the following basic events:

- Failure to restore valves to required positions concerning valves: V-101, 102, 103, 105, 107,112
- Failure to restore charging water flow path
- Failure to restore valve V-115 in the charging water system
- Failure to restore valve V-113 in the charging water system.

The THERP method provides error probability values for generic tasks and also describes the process used to modify these rates depending on specific performance shaping factors (PSFs) involved in the task being analyzed [20]. Performance shaping

factors are multiplicative factors that are applied to modify the nominal human error probability value in order to reflect the actual performance situation. For example, if the labeling scheme at a particular plant is poor, the human error probability value will increase. Conversely, if maintenance procedures are particularly good, the probability of some errors can be decreased by applying a PSF that modifies the human error probability from its nominal value based upon the adequacy of the procedures being used.

This method requires the performance of four steps [21]. The first step involves defining the task, determining what constitutes failure, and what human actions can lead to this failure. In this study, the task of interest is failure to restore specific valves in the HCU system to their proper alignments. Figure 4.4 shows a tree diagram that can be constructed in order to represent possible sequences of successes and failures in performing different subtasks. Events A, B, and C are the first, second, and third tasks that are performed. The solid lines and lower case letters represent success and the broken lines and capital letters represent failure.

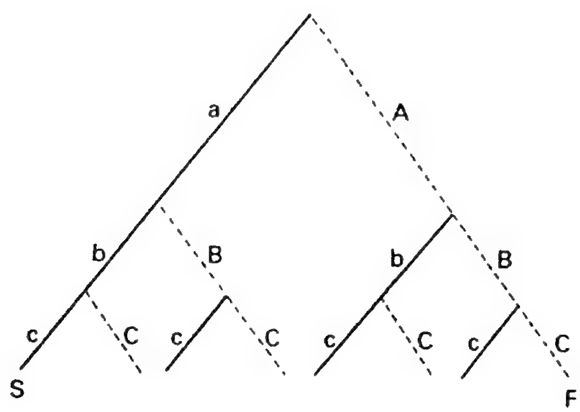


Figure 4.4 Example of THERP Tree Event Combination Diagramming for Events A, B, and C. [20]

The next step requires the determination of basic error rates relevant to the tree in Figure 4.4. The estimated error rates are obtained from Swain, et al. (1980). Because these basic human error rates are obtained from performance under average industry conditions, the third step incorporates the effects of PSFs to account for stress, work

environment factors, etc. The final step involves summing the individual sequence probabilities for the failure sequences in the THERP tree in order to obtain the value of the probability of failure for the task.

For this study, we utilize the HEP concept concerning the event, failure to restore HCU system valve configuration, as calculated from Credit, et. al (1992). The HEP accounts for five factors that affect the likelihood of human error during maintenance:

- whether relevant procedures are available and used
- quality of the procedures
- whether maintenance technicians are trained on the specific task
- whether a person from the Quality Control department performs a second check on the maintenance work
- whether post-maintenance testing is done.

Figure 4.5 shows the possible combinations of the above factors and the HEPs associated with each combination. The human error probabilities (HEP) and error factors (EF) are obtained from Tables 4.1-4.3 (adopted from Swain, et al. (1980)).

"The human error rates obtained through use of Figure 4.5 are determined by multiplying a basic human error probability by reduction factors that account for the five factors above. For example, Table 4.2 is used to quantify the human error rate when the operators use procedures that are above average quality. The value for this parameter is 0.002[1]. The reduction factors for the other branches are quantified using Table 4.3. For example, Table 4.3 presents human error rates for failing to detect errors made by others. For checking routine tasks using written materials, a human error rate of 0.1 is given. For checks that involve active participation, e.g., post maintenance testing, an error rate of 0.01 is given." [21] Table 4.4 presents the human error probabilities (HEP) and error factors (EF) used in estimating the human error rates underlying Figure 4.5. In this study,

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[1] This value is derived using entries from Table 6.2. This Table gives a human error probability value of 0.001 for an error of omission when using procedures that consist of short lists and check-off provisions. It is assumed that this is an optimal form for the procedure. It is further assumed that an error of commission is always possible and that the human error probability value in this case is also 0.001. Therefore, the total error rate is 0.001+0.001=0.002. [21]

we utilized the HEP of $2x10^{-6}$ to reflect use of quality procedures, adequate training on the task, second-check, and post-maintenance testing.

Estimated HEPs related to failure of administrative control

Item	Task	HEP	EF
(1)	Carry out a plant policy or scheduled tasks such as periodic tests or maintenance performed weekly, monthly, or at longer intervals	.01	5
(2)	Initiate a scheduled shiftly checking or inspection function*	.001	3
	Use written operations procedures under		
(3)	normal operating conditions	.01	3
(4)	abnormal operating conditions	.005	10
(5)	Use a valve change or restoration list	.01	3
(6)	Use written test or calibration procedures	.05	5
(7)	Use written maintenance procedures	.3	5
(8)	Use a checklist properly**	.5	5

*Assumptions for the periodicity and type of control room scans are discussed in Chapter 11 in the section, "A General Display Scanning Model." Assumptions for the periodicity of the basic walk-around inspection are discussed in Chapter 19 in the section, "Basic Walk-Around Inspection."

**Read a single item, perform the task, check off the item on the list. For any item in which a display reading or other entry must be written, assume correct use of the checklist for that item.

Table 4.1—Estimated HEPs Related to Failure of Administrative Control [22]

Estimated probabilities of errors of omission per item of instruction when use of written procedures is specified*

Item**	Omission of item:	HEP	EF
	When procedures with checkoff provisions are correctly used†:		
(1)	Short list, ≤10 items	.001	3
(2)	Long list, >10 items	.003	3
	When procedures without checkoff provisions are used, or when checkoff provisions are incorrectly used††:		
(3)	Short list, ≤10 items	.003	3
(4)	Long list, >10 items	.01	3
(5)	When written procedures are available and should be used but are not used††	.05‡	5

*The estimates for each item (or perceptual unit) presume zero dependence among the items (or units) and must be modified by using the dependence model when a nonzero level of dependence is assumed.

**The term "item" for this column is the usual designator for tabled entries and does not refer to an item of instruction in a procedure.

†Correct use of checkoff provisions is assumed for items in which written entries such as numerical values are required of the user.

††Table 16-1 lists the estimated probabilities of incorrect use of checkoff provisions and of nonuse of available written procedures.

‡If the task is judged to be "second nature," use the lower uncertainty bound for .05, i.e., use .01 (EF = 5).

Table 4.2—Estimated Probabilities of Errors of Omission per Item of Instruction When Use of Written Procedures is Specified [22]

Estimated probabilities that a checker will fail to detect errors made by others*

Item	Checking Operation	HEP	EF
(1)	Checking routine tasks, checker using written materials (includes over-the-shoulder inspections, verifying position of locally operated valves, switches, circuit breakers, connectors, etc., and checking written lists, tags, or procedures for accuracy)	.1	5
(2)	Same as above, but without written materials	.2	5
(3)	Special short-term, one-of-a-kind checking with alerting factors	.05	5
(4)	Checking that involves active participation, such as special measurements	.01	5
	Given that the position of a locally operated valve is checked (item 1 above), noticing that it is not completely opened or closed:	.5	5
(5)	Position indicator** only	.1	5
(6)	Position indicator** and a rising stem	.5	5
(7)	Neither a position indicator** nor a rising stem	.9	5
(8)	Checking by reader/checker of the task performer in a two-man team, <u>or</u> checking by a <u>second</u> checker, routine task (no credit for more than 2 checkers)	.5	5
(9)	Checking the status of equipment if that status affects one's safety when performing his tasks	.001	5
(10)	An operator checks change or restoration tasks performed by a maintainer	Above HEPs ÷ 2	5

*This table applies to cases during normal operating conditions in which a person is directed to check the work performed by others either as the work is being performed or after its completion.

**A position indicator incorporates a scale that indicates the position of the valve relative to a fully opened or fully closed position. A rising stem qualifies as a position indicator if there is a scale associated with it.

Table 4.3—Estimated Probabilities That a Checker Will Fail to Detect Errors Made by Others [22]

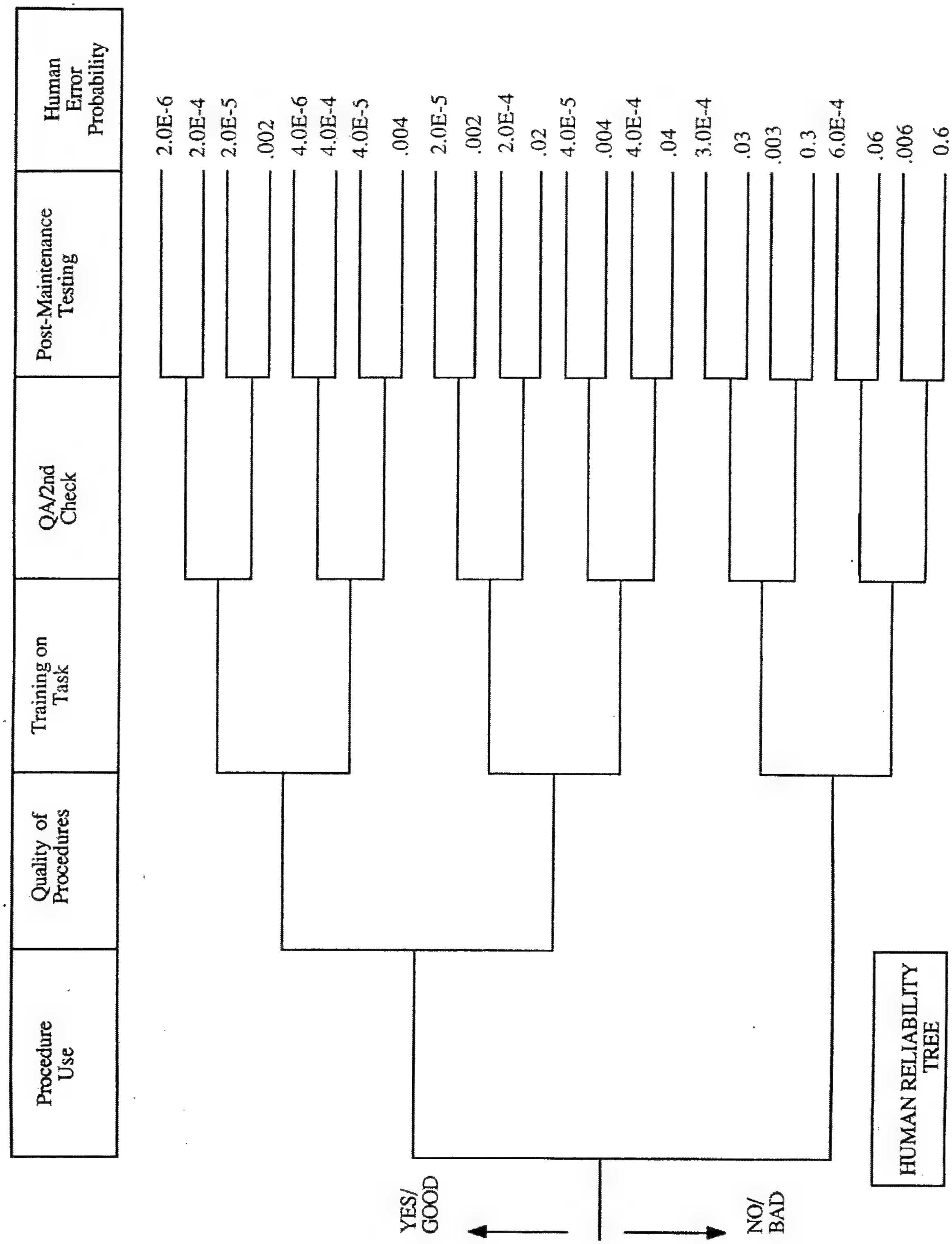


Figure 4.5—Human Reliability Tree [21]

Decision Analysis and Multi-Attribute Utility Theory

5.1 Introduction

Like most electric utility companies entering economic deregulation, the objectives of TEPCO concerning this maintenance study are as follows: [23]

1. To shorten the duration of outages

2. To assure that maintenance takes place year-round, employing workers from the local community year-round, thus improving relations with the local government and public

3. To enhance the competitiveness and safety of the nuclear power plants of TEPCO from the perspective of cost, using risk information.

In order to achieve these objectives, decisions must be made in a balanced and systematic way, using risk information, traditional safety approaches (i.e. defense in depth), and taking into account factors such as economics, stakeholder relations, and safety.

Decision analysis is a means by which decision options can be formulated and ranked in a structured manner by "1) enumerating the choices available to the decision maker, 2) characterizing relative uncertainties, 3) quantifying the relative desirability of outcomes, and 4) providing rules for ranking the decision options, thus helping the decision maker to select the "best" option." [23]

5.2 Multi-Attribute Utility Theory (MAUT)

In order to make the right decision that will satisfy many objectives, MAUT is utilized as the means by which decision options are analyzed and ranked according to favorability. In MAUT, the measure of favorability is called the "Performance Index," (also known as the "expected utility" of the decision option) and it is calculated for each

decision option considered. A PI is the sum of the weights of performance measures (PM), which are determined through an analytical process (known formally as Analytical Hierarchy Process (AHP)), multiplied by the utility of each PM with respect to each option. We use this method to analyze the decision options available to HCU maintenance at TEPCO. Equation 5.1 [4] summarizes the integration of decision factors and Figure 5.1 shows their hierarchy, where

$$PI_j = \sum w_i \cdot u_{ij}$$

PIj = performance index for the j^{th} decision option

w_i = weight of the i^{th} PM

u_{ij} = the utility for the i^{th} PM given by the j^{th} decision option

Equation 5.1

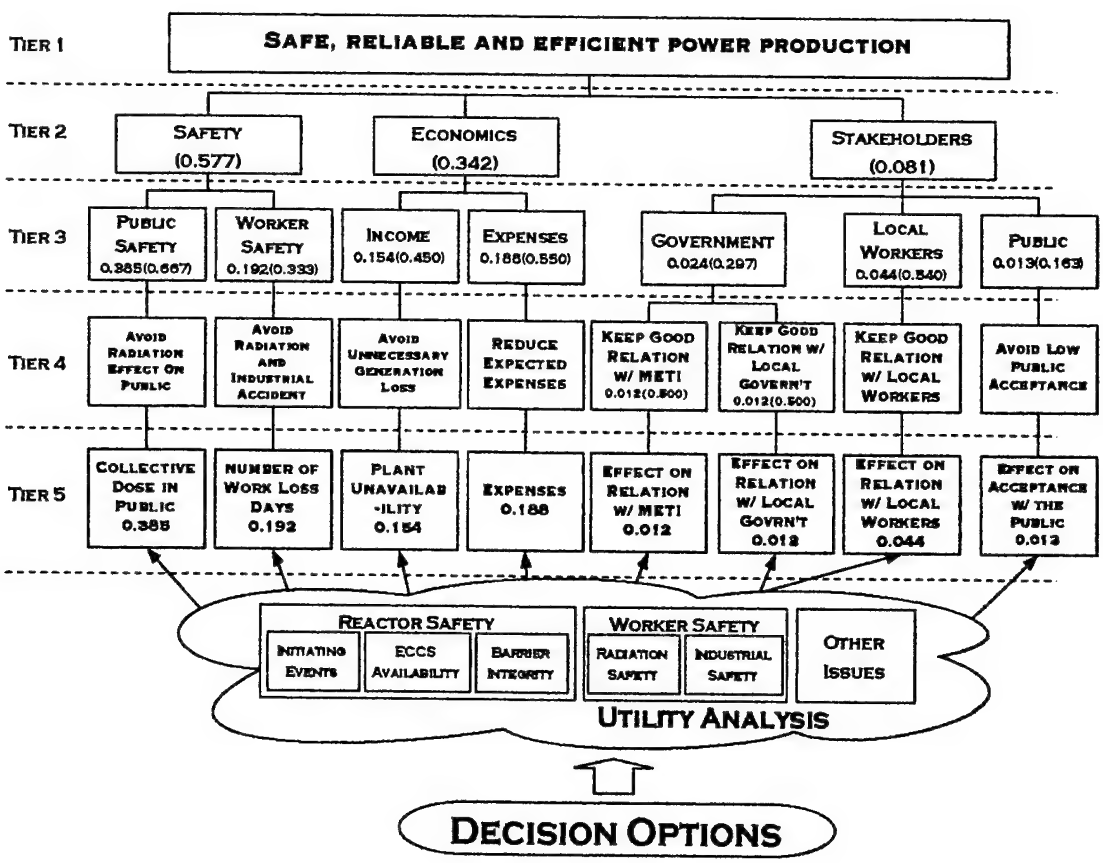


Figure 5.1— Overall Methodological Structure for Characterizing TEPCO's Decision Making Values [4]

5.2.1. Value Tree

The Value Tree shown in Figure 5.1 is a hierarchical structure of objectives to be achieved via the available decision options. The overall objective, "Safe, Reliable, and Efficient Power Production," is located in Tier 1 of the tree. The tiers below decompose the higher level objectives concerning how the decision maker plans to achieve the overall objective. For example, to achieve "Safe, Reliable, and Efficient Power Production," one must consider safety, cost, and stakeholder relations (Tier 2). Safety, cost, and stakeholder relations can be further broken down to public safety, worker safety, income, government, etc. Tier 4 represents concrete goals that the decision maker wants to achieve in terms of the factors considered, and Tier 5 provides a means for quantifying the achievement of each goal above. The attributes in Tier 5 are termed Performance Measures (PM), and Table 5.1 provides a definition of each Performance Measure.

Table 5.1: Definitions of Performance Measures Used in TEPCO Project [24]

Name of PM	Definition
Public Dose	Cumulative dose among the public, which would be exclusively derived from a massive release of radioactive materials due to an accident (does not include any worker casualties).
Work Loss Days	Lost work-days calculated by the definition in "Labor Standard Act", which includes contribution of both work resulting from a release of radioactive materials and from an industrial accident
Plant Unavailability	Expected power loss due to reactor shutdown and/or power suppression, converted into loss of days at full power generation using the following equation: PU = (Missed electricity production) / {(Plant Electric Rated Power) * 24 hrs}
Expenses	Cost of maintenance and operation, namely maintenance, personnel, supplies and fuel costs as well as depreciation and related taxes, and expected cost in case of undesirable occurrences (ex. unplanned shutdown) resulting from the decision being made.
Relation w/ METI	Influences upon relationship between TEPCO and METI by the decision being made. (Very Good, Good, Weak, Bad, Very Bad)
Relation w/ Local Government	Effect upon mood between TEPCO and local government(s) with respect to matters other than "stable employment" and "public acceptance" by the decision being made. (Very good, Good, Weak, Bad, Very Bad)

Work Load	Expected number of workers to be shifted to online in the next four operational cycles suggested by the decision being made (Number of workers)
Media Coverage	Expected media reaction on the decision being made (Very Good, Good, Weak, Bad, Very Bad)

5.2.2 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) allows the decision maker to assign a weight to each performance measure, enabling the decision maker to prioritize and rank each PM. Pairwise comparisons are utilized in the AHP in order to determine the weight of each item as the decision maker compares two items at a time and determines which is more important with respect to the other. The scale he uses is shown in Table 5.2. For example, objectives on each tier of the value tree are compared and rated with respect to other objectives in the same tier. This process is iterated until Tier 5 is reached where the PMs are weighted against each other. The weights are finally calculated using computer software such as "Expert Choice." The weights determined for each PM are shown in Figure 5.1 in Tier 5 below each PM. These weights apply for the example assuming that the decision makers place 50% of importance to Safety, 25% to Economics, and 25% to Stakeholder Relations.

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another.
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice.
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between adjacent scale values	Used when compromise is needed.

Table 5.2: Comparison scale to Determine Weight of Performance Measures [24]

5.2.3 Constructed Scales and Utility Functions

For PMs that are quantifiable, the decision maker will set a range for each PM that is practical and carefully considers the consequences of the decision to be made. This range is divided into several levels (designated by a scale number), and a pairwise comparison is made between the levels to determine individual weights. The weights are then converted into utility values that range from 0 to 1 using the following equations:

$$u = a + b * w, \text{ where}$$
$$a = -b * (\text{smallest weight}), \text{ and}$$
$$b = 1 / \{ (\text{biggest weight}) - (\text{smallest weight}) \}.$$

Generally the term u represents the utility, but in this project, we wish to express the decision maker's degree of dislike for a consequence in terms of the PMs, therefore u actually represents the "disutility" of the decision.

For PMs that are not objectively quantifiable such as "Relation with METI," the decision maker constructs scales that quantitatively represent each state of the PM and then a disutility is assessed for each scale value. In summary, a high disutility correlates with low desirability (i.e. a disutility of unity equates to the least desirable consequence). [24]

5.3 Application to HCU Maintenance Options

In this study, MAUT is utilized to provide a ranking of the desirability of the following decision options for HCU maintenance:

1. On-line HCU maintenance with no change in outage duration
2. Off-line HCU maintenance with no change in outage duration
3. On-line HCU maintenance with a shortened outage
4. Off-line HCU maintenance with a shortened outage.

In reference to the value tree, these "Decision Options" are considered, and a "Utility Analysis" is performed in order to determine the impact of a specific Decision Option upon each Performance Measure. The "Utility Analysis" involves the evaluation of the values of utilities using methods of Probabilistic Risk Assessment (PRA) and expert judgment. In this study, we chose to use fault trees to determine the values of the top event probabilities for six different HCU system failures:

Top Event 1: Excessive Scram Time
Top Event 2: Failure to Scram
Top Event 3: Inadvertent Rod Motion Inward
Top Event 4: Inadvertent Rod Motion Outward
Top Event 5: Failure to Move Control Rod Inward
Top Event 6: Failure to Move Control Rod Outward.

For each decision option, the effect of occurrence of the respective six top events on each of the performance measures was considered, values of the disutilities formulated, and expected disutility values calculated based upon knowledge of the top event probabilities. Alternately, the effect of no top event occurring upon each performance measure was also considered. These expected disutility values are then multiplied by the weight of each PM and summed in order to obtain the values of the overall performance index value for the decision option under consideration. The option having the lowest overall performance index value is the most desirable. The next section describes in detail the use of MAUT to quantify the effects of the HCU maintenance options considered on the Performance Measures.

Quantitative Impact of HCU Maintenance Options Upon Performance Measure Values

6.1 Introduction

In an effort to boost competitiveness in a deregulated electricity market, US nuclear power plant utilities were forced to change how their plants are maintained and operated. One change that has produced tangible benefits was the shift of HCU maintenance from being performed off-line (during outages) to being performed on-line. This change shortened outage durations, reduced outage maintenance costs, and allowed plant personnel to be utilized year-round for the performance of on-line HCU maintenance. Although no formal risk analysis was performed by the US in order to justify the shift, the benefits realized greatly outweighed the risks involved. This study provides a quantitative measure of the desirability of on-line maintenance from the perspective of TEPCO, and it also serves as a model for formal analysis of various decision options.

This section demonstrates how MAUT can be utilized to provide a rank-ordering of the attractiveness of the decision options available in this study. The decision options available to decision makers at TEPCO are the following:

1. On-line HCU maintenance with no change in outage duration
2. Off-line HCU maintenance with no change in outage duration
3. On-line HCU maintenance with a shortened outage
4. Off-line HCU maintenance with a shortened outage.

The use of MAUT allows decision makers to consider not only the effects upon safety and economics but also the effects on stakeholder relations. This analysis can be used as an aid to 1) enhance consensus building, 2) provide a systematic method for processing a large amount of information, 3) provide formal rules for quantifying preferences, and 4)

enhance the decision-making process by improving communication between decision makers. [23]

6.2 Overview of Quantitative Analysis Approach

Figure 6.1 is a flowchart illustrating the quantitative analysis approach taken in the use of MAUT to rank the desirability of various HCU maintenance options. The first step in the formal analysis is to list the decision options available. In reference to the value tree, results of this evaluation appear at the very bottom tier. In this case study, the options available are different combinations of on-line or off-line HCU maintenance under the conditions of a long or short outage. The long outage cases assume that TEPCO maintains its current outage duration (90 days on average). The short outage cases assume that TEPCO becomes more efficient in the accomplishment of critical path items and shifts some non-critical path maintenance items to being performed on-line.

The next step considers each decision option and its effect on the values of the performance measures of the value tree. On the value tree, this is the "Utility Analysis" under Tier 5. This step is actually the most complex in that several calculations must be performed prior to calculating the overall performance index. These calculations include the determination of the values of the basic event and top event probabilities from NPRDS data, of human error probabilities, and of expected disutility values. Because there were no objective information available regarding the consequences of the occurrence or non-occurrence of an HCU top-event, the majority of our results are based upon the expert judgment of TEPCO engineers. The overall performance index values are calculated using the expected disutility values and performance measure weights. The decision option having the lowest overall PI value is the most desirable.

The last step considers changes in the weights of the performance measures to reflect differences in the preferences of the decision makers.

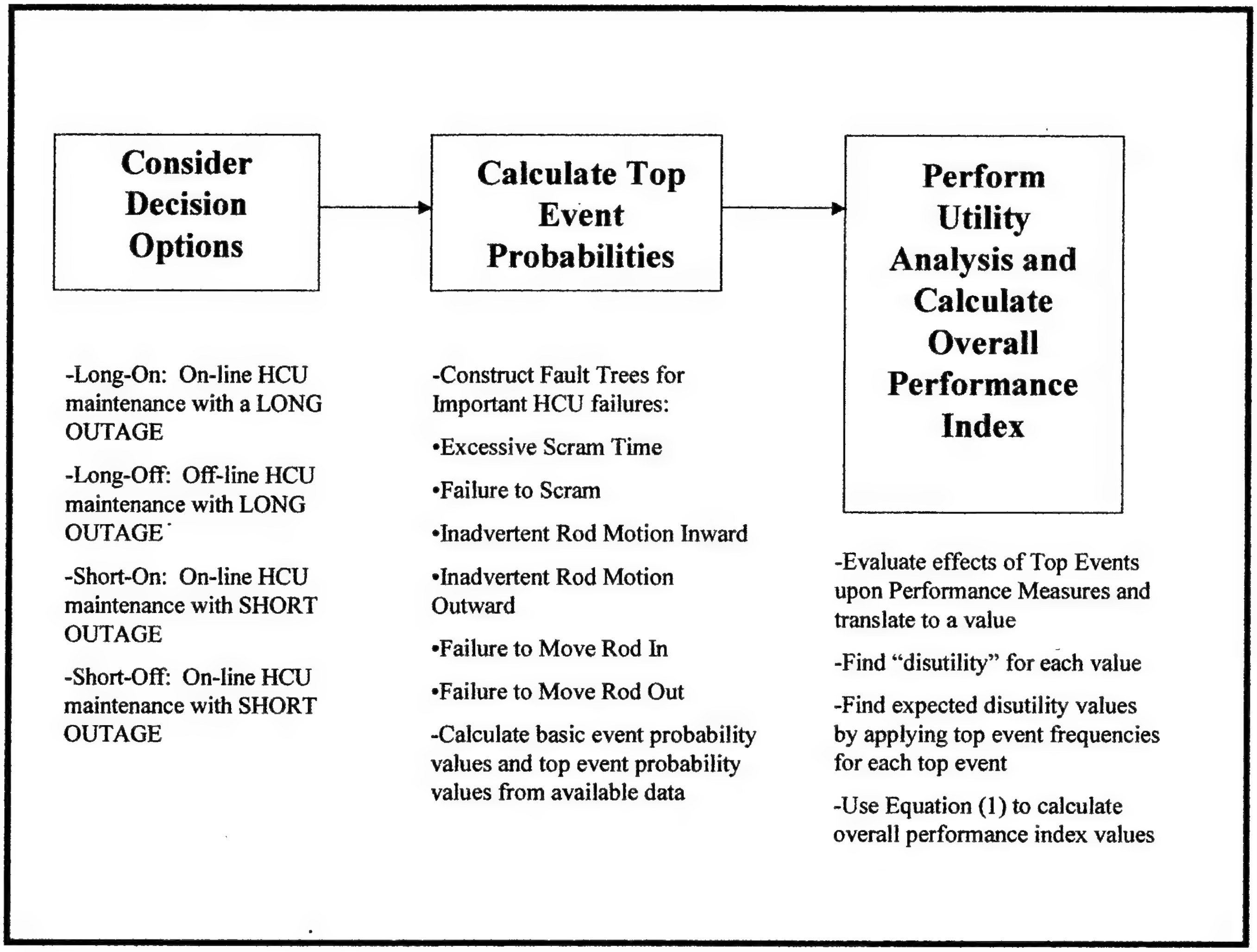


Figure 6.1—Quantitative Analysis Approach to Rank Desirability of HCU Maintenance Options

6.3 Method of Analysis

This section provides an overview of how the "Utility Analysis" is performed and the overall performance index values determined for each decision option.

6.3.1 Calculate Potential HCU Failure Basic Event Probabilities

6.3.1.1 Sources of Data and Assumptions

As discussed in Section 4.5, the basic event probabilities were determined from NPRDS data that spanned from 1978-1996. Although data was not available for a few basic events, basic event probabilities could still be assigned by assuming that similar events had the same basic event probabilities. For those events where data was not available and there were no similar events for which the number of occurrences could be assumed, we assigned one occurrence during the report period.

6.3.1.2 Basic Events Attributed to Human Error

The following basic events are directly attributed to human error:

-SSPV fail to vent due to improper substances used during maintenance
-SSPV fail to vent due to parts incorrectly installed/improper rebuild
-SSPV fail to vent due to adjustment errors
-Scram Inlet valve fails to move due to parts incorrectly installed/improper rebuild
-Scram Inlet valve fails to move due to adjustment errors
-Scram Outlet valve fails to move due to improper substances used during maintenance
-Scram Outlet valve fails to move due to parts incorrectly installed/improper rebuild
-Scram Outlet valve fails to move due to adjustment errors
-Nitrogen volume failure to detect leaks due to failure of operators*
-Accumulator volume failure to detect leaks due to failure of operators*
-Check valve failure to due parts incorrectly installed
-Directional Control Valve failure due to improper parts installation
-Directional Control Valve failure due to improper adjustment
-Charging water failure to restore flow path*
-Charging water failure to restore V-115 *
-Charging water failure to restore V-113*

-Failure to restore valves to required positions

V-101*
V-102*
V-103*
V-105*
V-107*
V-112*.

For those items followed by asterisks, basic event probabilities were determined using the Technique for Human Error Rate Prediction (THERP). The remaining basic event probabilities were found from NPRDS data or from the assumptions stated above in Section 6.3.1.1.

To account for the increased stress levels experienced by maintenance personnel and operators, a performance shaping factor (PSF) of (x2) was applied to the basic events attributed to human error. This factor was determined from Reference 22 for moderately high stress level conditions.

6.3.2 Calculate HCU System Failure Top Event probabilities

Using the fault trees for the following top events of interest, the top event probabilities were determined by applying the rules of Boolean algebra:

Top Event 1: Excessive Scram Time
Top Event 2: Failure to Scram
Top Event 3: Inadvertent Rod Motion Inward
Top Event 4: Inadvertent Rod Motion Outward
Top Event 5: Failure to Move Control Rod Inward
Top Event 6: Failure to Move Control Rod Outward

Appendix A shows in detail the calculation of individual top event probabilities.

As seen in Appendix A, there are two sets of top event probabilities: one is the "BASELINE" case and the other is the "STRESS" case where a performance shaping factor of (x2) was applied to basic events attributed to human error. The "STRESS" case

top event probabilities will be utilized for the "Short-Off" decision option (Off-line HCU Maintenance with a shortened outage). We made the assumption that stress levels will be much higher in the case of off-line HCU maintenance during a shorter outage because workers have not only critical path work, but also HCU maintenance to complete in a compressed time period.

6.3.3 Formulate Decision Options

The decision options and assumptions for each are as follows:

Long-On: On-line HCU maintenance with no change in outage duration

--HCU maintenance is performed on-line with no change in outage duration. The average outage duration for TEPCO plants is 90 days.

--The BASELINE top event probabilities are used because there is no difference in stress levels when doing HCU maintenance on-line or off-line when the outage durations are the same for either option.

Long-Off: Off-line HCU maintenance with no change in outage duration

--HCU maintenance is performed off-line with no change in outage duration. The average outage duration for TEPCO plants is 90 days.

--The BASELINE top event probabilities are used because there is no difference in stress levels when doing HCU maintenance on-line or off-line when the outage durations are the same for either option

Short-On: On-line HCU maintenance with a shortened outage

--HCU maintenance is performed on-line with a shortened outage duration.

--We assume the outage duration was shortened by increased efficiency in completing critical path work items and by shifting selected non-critical path maintenance on-line. The assumed shortened outage duration is 60 days.

--The BASELINE top event probabilities are used because there is no added stress when HCU maintenance is performed on-line with a shortened outage.

Short-Off: Off-line HCU maintenance with a shortened outage

--HCU maintenance is performed off-line with a shortened outage duration.

--We assume the outage duration was shortened by increased efficiency in completing critical path work items and by shifting selected non-critical path maintenance on-line. The assumed shortened outage duration is 60 days.

--The STRESS top event probabilities are used because the stress levels are moderately higher when performing HCU maintenance off-line during a shortened outage.

6.3.4 Calculate overall performance index values for each decision option considering both occurrence and avoidance of system failure

6.3.4.1 Formulate Values for each Performance Measure

In this step, each decision option's effect upon the performance measures is evaluated in the event that each top event occurs and also for the situation in which no top event occurs. Table 6.1 and 6.2 demonstrate how this evaluation is formatted for both the long and short outage cases. Assumptions were made for the following performance measures:

1. Public Casualty (PC): Since Loss of Reactivity Control is an initiating event with a very low probability of occurrence [26], we assumed that our decision options for HCU maintenance would have a negligible effect upon Core Damage Frequency (CDF) and to Large Early Release Frequency (LERF). Therefore, the values assigned are equal to zero for all four decision options and each occurrence and non-occurrence of a top event.

2. Worker Casualty (WC): Because maintenance on HCU components involves small components located relatively close to each other and requires no industrial equipment (ie, lifts, ladders, etc), the effect on the number of worker casualties is negligible. Therefore, the values assigned are zero for all four decision options and each occurrence and non-occurrence of a top event.

3. Plant Unavailability (PU): For the long outage cases, we assumed that the plant would be out of service for 90 days in order to reflect the length of time that the plant is down for outage maintenance. In the short outage cases, the plant would be out of service for 60 days. In the cases where a top event occurs, the additional unavailability would be 14 days, giving a total plant unavailability of 104 days and 74 days for the long outage and short outages cases, respectively.

4. Repair Cost (Cost): For each decision option should a top event occur, the assumed cost to fix the problem in the HCU system that caused the top event is approximately Y2.9E6. The cost associated with no top event occurring is zero.

5. Worker Load: For the "Long-On" case where a top event does not occur, the assumed worker load is equal to eight in order to account for the workers required to perform on-line HCU maintenance. In the event that a top event occurs in the "Long-On" case, an additional two workers would be required to fix the problem, giving a total of 10 workers. For the "Long-Off" case, if no top event occurs, worker load is zero; but when a top event does occur, two workers will be required to fix the problem that caused the top event. For the "Short-On" case, the worker load for the "no top-event" case is equal to 18 to account for the number of workers needed to perform HCU and other non-critical path maintenance on line. In the case of a top event occurring for the "Short-On" case, an additional two workers are required. For the "Short-Off" case, if no top event should occur, 10 workers would be needed only to perform the non-critical path maintenance that was shifted from being performed off-line to being performed on-line. In the case of a top event occurring for the "Short-Off" case, an additional 2 workers would be needed, giving a total of 12 workers.

6. Relationships with METI (METI), Local Government (LG), and Media Coverage (MC):

For these performance measures, the expected reaction by each entity is assigned for each decision option under the circumstances of a top event occurring and not occurring.

However, this assigned value is not used to assign a unique disutility value since the expected reactions of the respective stakeholders are uncertain and may vary. They are treated probabilistically. Section 6.3.4.2 describes how probability mass functions were assigned for METI, LG, and MC reactions to account for the uncertainty in stakeholder reactions.

6.3.4.2 Formulate Disutilities for Each Value

The corresponding disutilities for the values assigned in the previous section can be found by using the graphs of Sato, et al. (Ref 25). These graphs are Figures 6.2-6.9. For the performance measures METI, LG, and MC, conditional probability values were formulated to account for the uncertainties in the reactions by each of these stakeholders to the decision options and occurrence/non-occurrence of top events. Tables 6.3-6.8 demonstrate how the expected values of the disutilities were determined. For example, looking at Table 6.3, for the "Long-On" example in the case of Top Event 1 occurring, there is a probability of 0.6 that the relationship with METI will become "BAD," a probability of 0.3 that it will become "WEAK," and a probability of 0.1 that it will become "VERY BAD." The corresponding disutility values (from Figure 6.6) are 0.42, 0.2, and 1, respectively. Using the following relationship,

$$\textbf{Expected Disutility Value} = \sum_{\text{i outcome states}} \textbf{P}\,(\textbf{S}_i/\textbf{T}) \ \textbf{X} \ \textbf{Disutility}\,(\textbf{S}_i) \ \textbf{[27]}$$

where P (S_i/T) is the probability of state, (S_i), given that a Top Event Occurs and Disutility (S_i) is the disutility value of a given state (from Figure 6.2-6.9).

The expected value of the disutility of METI relationship, considering the "Long-On" case with Top Event 1 occurring, is 0.41. These expected values of disutilities are used in Tables 6.10-6.11 for both the long outage and short outage cases.

The following assumptions were made in our work in order to establish the differences in the probability mass functions between the decision options:

1. Comparing the "Long-On" case and "Long-Off" case we use the following assumptions:

--The reaction by METI will be slightly worse in the "Long-On" case than in the "Long-Off" case because the expectations for good outcomes are greater when on-line HCU maintenance is accepted by the regulator, resulting in a more negative outcome should a top event occur.

--The reaction by local government will be slightly worse in the "Long-Off" case because there is a lack of workers employed year-round. Thus, should a top event occur, the LG reaction in the "Long-Off" case will be more negative compared to the "Long-On" case.

--Media Coverage will be more negative should a top event occur in the "Long-On" case because the media will be suspicious and wary of on-line HCU maintenance.

--Within the "Long-On" case, the LG reaction will be slightly worse than METI reaction due to the local government's suspicion to the new HCU on-line maintenance practice.

--If no top event occurs, the LG reaction in the "Long-On" case will be slightly better than that in the "Long-Off" case because on-line HCU maintenance employs workers year-round and does not adversely affect plant safety.

2. Comparing the "Short-On" case and "Short-Off" case:

--The reaction by METI will be slightly worse in the "Short-On" case than in the "Short-Off" case because the expectations are greater when on-line HCU maintenance is accepted, resulting in a more negative outcome should a top event occur.

--The reaction by local government will be slightly worse in the "Short-Off" case because there are a fewer number of workers employed year-round. Thus, should a top event occur, the LG reaction in the "Long-Off" case will be more negative compared to the "Short-On" case.

--If no top event occurs, the reactions by METI, LG, and the media will be more positive for the "Short-On" case because on-line HCU maintenance has enabled TEPCO to achieve all of its goals: reducing the outage duration, employing more workers year-round, and maintaining or improving plant safety.

3. Comparing the "Long-On" case and "Short-On" case:

--The METI response will be slightly worse for the "Short-On" case than the "Long-On" case because the level of disappointment will be greater if a top event occurs. This is due to the greater amount of scrutiny that METI experiences from the decision to expand on-line maintenance.

--The LG response to a top event occurrence will be worse for the "Long-On" case than the "Short-On" case because there are more workers employed on-line in the "Short-On" case, quelling LG suspicion to the new practice.

--Media Coverage, should a top event occur, is more negative for the "Short-On" case than the "Long-On" case because the media see expansion of on-line maintenance as negatively affecting plant safety.

4. Comparing the "Long-Off" case and "Short-Off" case:

--The METI response will be slightly worse for the "Short-Off" case than the "Long-Off" case because of the greater scrutiny is faces.

--The LG reaction in the "Short-Off" case would not be as severe as the "Long-Off" case due to the greater number of workers employed on-line.

-- Media Coverage, should a top event occur, is more negative for the "Short-On" case than the "Long-On" case because the media see expansion of on-line maintenance as negatively affecting plant safety.

6.3.4.3 Calculation of Expected Disutility Values for each System Outcome and for each Performance Measure

The expected disutility values for each System Outcome and for each performance measure are calculated using the values of the disutilities given in Tables

6.10-6.11 and multiplied by the respective probability of the given top event occurring or not occurring (P=1). The top event probabilities that are utilized are as delineated in Section 6.3.3. Finally, the expected disutility value for each top event is summed for each performance measure. Figure 6.11 shows how this is done. The expected disutilities in the highlighted column are summed to obtain an expected value of 2.05E-03.

6.3.4.4 Calculation of the Overall Performance Index Values

The overall performance index value is calculated using the following equation:

$$PI_j = \sum w_i \cdot u_{ij}$$

PIj = performance index for the j^{th} decision option

w_i = *weight* of the i^{th} PM

u_{ij} = the utility for the i^{th} PM given by the j^{th} decision option and the kth top event outcome

The decision option having the lowest overall performance index is the most desirable. In order to account for the changing preferences of the decision maker, this calculation was carried out using different weights. The weights given in Section 5.2.2 were evaluated with the assumption that the decision makers would distribute their preferences as follows: 50% to safety, 25% to economics, and 25% to relations to stakeholders. In a sensitivity analysis we also considered the following distribution of preferences:

- 33/33/33
- 60/20/20
- 70/20/10
- 45/45/10
- 75/20/5

The corresponding individual weights for each performance measure, given the overall weight preferences for safety, economics, and stakeholder relations is shown in Table 6.9. 33/33/33, 50/25/25, etc. are High Level Importance Weights and the numbers below each performance measure (PC, WC, PU, etc.) are Individual Metric Importance Weights.

	INDIVIDUAL METRIC IMPORTANCE WEIGHTS FOR EACH PM							
HIGH LEVEL IMPORTANCE WEIGHTS	PC	WC	PU	COST	METI	LG	WL	MC
33/33/33	0.22	0.11	0.149	0.181	0.066	0.066	0.132	0.066
50/25/25	0.333	0.167	0.113	0.138	0.05	0.05	0.01	0.05
60/20/20	0.4	0.2	0.09	0.11	0.02	0.04	0.08	0.04
70/20/10	0.466	0.234	0.09	0.11	0.02	0.02	0.04	0.02
45/45/10	0.3	0.15	0.203	0.247	0.02	0.02	0.04	0.02
75/20/5	0.5	0.251	0.09	0.11	0.01	0.01	0.02	0.01

Table 6.9—Weights of Individual Performance Measures, given Overall Decision Maker Preferences concerning Safety, Economics, and Stakeholder Relations [28]

DECISION OPTION & TOP EVENTS

VALUES FOR PERFORMANCE MEASURES
IN CASE OF TOP EVENT OCCURRING

LONG-ON	PC	WC	PU	COST	METI	LG	WL	MC
TE1	0	0	104	2.85E+06	Weak	Weak	10	Bad
TE2	0	0	104	2.85E+06	Bad	Bad	10	Bad
TE3	0	0	104	2.85E+06	Weak	Weak	10	Bad
TE4	0	0	104	2.85E+06	Bad	Bad	10	Bad
TE5	0	0	104	2.85E+06	Bad	Bad	10	Bad
TE6	0	0	104	2.85E+06	Weak	Weak	10	Bad
LONG-OFF	**PC**	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
TE1	0	0	104	2.85E+06	Weak	Bad	2	Weak
TE2	0	0	104	2.85E+06	Bad	Very Bad	2	Weak
TE3	0	0	104	2.85E+06	Weak	Bad	2	Weak
TE4	0	0	104	2.85E+06	Bad	Very Bad	2	Weak
TE5	0	0	104	2.85E+06	Bad	Very Bad	2	Weak
TE6	0	0	104	2.85E+06	Weak	Bad	2	Weak

DECISION OPTION

VALUES FOR PERFORMANCE MEASURES
IN CASE OF NO TOP EVENT OCCURRING

	PC	WC	PU	COST	METI	LG	WL	MC
LONG-ON	0	0	90	0	Good	Good	8	Good
LONG-OFF	0	0	90	0	Good	Good	0	Good

Table 6.1—Values for Performance Measures (Long Outage Case)

DECISION OPTION & TOP EVENT	VALUES FOR PERFORMANCE MEASURES IN CASE OF TOP EVENT OCCURRING							
SHORT-ON	**PC**	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
TE1	0	0	74	2.85E+06	Weak	Weak	20	Bad
TE2	0	0	74	2.85E+06	Bad	Bad	20	Bad
TE3	0	0	74	2.85E+06	Weak	Weak	20	Bad
TE4	0	0	74	2.85E+06	Bad	Bad	20	Bad
TE5	0	0	74	2.85E+06	Bad	Bad	20	Bad
TE6	0	0	74	2.85E+06	Weak	Weak	20	Bad
SHORT-OFF	**PC**	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
TE1	0	0	74	2.85E+06	Weak	Bad	12	Weak
TE2	0	0	74	2.85E+06	Bad	Very Bad	12	Weak
TE3	0	0	74	2.85E+06	Weak	Bad	12	Weak
TE4	0	0	74	2.85E+06	Bad	Very Bad	12	Weak
TE5	0	0	74	2.85E+06	Bad	Very Bad	12	Weak
TE6	0	0	74	2.85E+06	Weak	Bad	12	Weak

DECISION OPTION	VALUES FOR PERFORMANCE MEASURES IN CASE OF NO TOP EVENT OCCURRING							
	PC	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
SHORT-ON	0	0	60	0	Good	Good	18	Good
SHORT-OFF	0	0	60	0	Good	Good	10	Good

Table 6.2—Values for Performance Measures (Short Outage Case)

LONG-ON

METI RELATIONSHIP

TOP EVENT 1 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.3	Weak	0.2
0.6	Bad	0.42
0.1	Very bad	1
<Disutility>		0.412

TOP EVENT 2 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.2	Weak	0.2
0.7	Bad	0.42
0.1	Very bad	1
<Disutility>		0.434

TOP EVENT 3 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.3	Weak	0.2
0.6	Bad	0.42
0.1	Very bad	1
<Disutility>		0.412

TOP EVENT 4 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.2	Weak	0.2
0.7	Bad	0.42
0.1	Very bad	1
<Disutility>		0.434

TOP EVENT 5 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.2	Weak	0.2
0.7	Bad	0.42
0.1	Very bad	1
<Disutility>		0.434

TOP EVENT 6 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.3	Weak	0.2
0.6	Bad	0.42
0.1	Very bad	1
<Disutility>		0.412

Expected Disutility Value = Σ P (S_i/T) X Disutility

LOCAL GOVERNMENT RELATIONSHIP

TOP EVENT 1 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.05	Weak	0.167
0.65	Bad	0.436
0.3	Very bad	1
<Disutility>		0.59175

TOP EVENT 2 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.75	Bad	0.436
0.05	Very bad	1
<Disutility>		0.4104

TOP EVENT 3 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.05	Weak	0.167
0.65	Bad	0.436
0.3	Very bad	1
<Disutility>		0.59175

TOP EVENT 4 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.75	Bad	0.436
0.05	Very bad	1
<Disutility>		0.4104

TOP EVENT 5 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.75	Bad	0.436
0.05	Very bad	1
<Disutility>		0.4104

TOP EVENT 6 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.05	Weak	0.167
0.65	Bad	0.436
0.3	Very bad	1
<Disutility>		0.59175

EFFECT ON MEDIA COVERAGE

TOP EVENT 1 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.75	Bad	0.482
0.2	Very bad	1
<Disutility>		0.57035

TOP EVENT 2 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.75	Bad	0.482
0.2	Very bad	1
<Disutility>		0.57035

TOP EVENT 3 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.75	Bad	0.482
0.2	Very bad	1
<Disutility>		0.57035

TOP EVENT 4 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.75	Bad	0.482
0.2	Very bad	1
<Disutility>		0.57035

TOP EVENT 5 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.75	Bad	0.482
0.2	Very bad	1
<Disutility>		0.57035

TOP EVENT 6 OCCURRING

P(S/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.75	Bad	0.482
0.2	Very bad	1
<Disutility>		0.57035

Table 6.3--Conditional Probabilities and Associated Disutilities of Stakeholder Reactions in case of Top Event Occurrence (Long-On)

LONG-OFF

METI RELATIONSHIP

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.075
0.45	Weak	0.2
0.5	Bad	0.42
0.04	Very bad	1
<Disutility>		0.34075

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.3	Weak	0.2
0.6	Bad	0.42
0.1	Very bad	1
<Disutility>		0.412

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.075
0.45	Weak	0.2
0.5	Bad	0.42
0.04	Very bad	1
<Disutility>		0.34075

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.3	Weak	0.2
0.6	Bad	0.42
0.1	Very bad	1
<Disutility>		0.412

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.3	Weak	0.2
0.6	Bad	0.42
0.1	Very bad	1
<Disutility>		0.412

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.075
0.45	Weak	0.2
0.5	Bad	0.42
0.04	Very bad	1
<Disutility>		0.34075

LOCAL GOVERNMENT RELATIONSHIP

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.7	Bad	0.436
0.1	Very bad	1
<Disutility>		0.4386

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.1	Weak	0.167
0.2	Bad	0.436
0.7	Very bad	1
<Disutility>		0.8039

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.7	Bad	0.436
0.1	Very bad	1
<Disutility>		0.4386

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.1	Weak	0.167
0.2	Bad	0.436
0.7	Very bad	1
<Disutility>		0.8039

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.1	Weak	0.167
0.2	Bad	0.436
0.7	Very bad	1
<Disutility>		0.8039

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.7	Bad	0.436
0.1	Very bad	1
<Disutility>		0.4386

EFFECT ON MEDIA COVERAGE

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.75	Weak	0.2
0.2	Bad	0.482
0.04	Very bad	1
<Disutility>		0.28725

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.75	Weak	0.2
0.2	Bad	0.482
0.04	Very bad	1
<Disutility>		0.28725

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.75	Weak	0.2
0.2	Bad	0.482
0.04	Very bad	1
<Disutility>		0.28725

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.75	Weak	0.2
0.2	Bad	0.482
0.04	Very bad	1
<Disutility>		0.28725

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.75	Weak	0.2
0.2	Bad	0.482
0.04	Very bad	1
<Disutility>		0.28725

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.75	Weak	0.2
0.2	Bad	0.482
0.04	Very bad	1
<Disutility>		0.28725

Table 6.4-- Conditional Probabilities and Associated Disutilities of Stakeholder Reactions in case of Top Event Occurrence (Long-Off)

SHORT-ON

METI RELATIONSHIP

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.05	Weak	0.2
0.65	Bad	0.42
0.3	Very bad	1
<Disutility>		0.583

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.2	Weak	0.2
0.75	Bad	0.42
0.05	Very bad	1
<Disutility>		0.405

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.05	Weak	0.2
0.65	Bad	0.42
0.3	Very bad	1
<Disutility>		0.583

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.2	Weak	0.2
0.75	Bad	0.42
0.05	Very bad	1
<Disutility>		0.405

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.2	Weak	0.2
0.75	Bad	0.42
0.05	Very bad	1
<Disutility>		0.405

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.05	Weak	0.2
0.65	Bad	0.42
0.3	Very bad	1
<Disutility>		0.583

LOCAL GOVERNMENT RELATIONSHIP

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.3	Weak	0.167
0.6	Bad	0.436
0.1	Very bad	1
<Disutility>		0.4117

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.7	Bad	0.436
0.1	Very bad	1
<Disutility>		0.4386

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.7	Bad	0.436
0.1	Very bad	1
<Disutility>		0.4386

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.75	Bad	0.436
0.05	Very bad	1
<Disutility>		0.4104

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.2	Weak	0.167
0.7	Bad	0.436
0.1	Very bad	1
<Disutility>		0.4386

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.3	Weak	0.167
0.6	Bad	0.436
0.1	Very bad	1
<Disutility>		0.4117

EFFECT ON MEDIA COVERAGE

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.2	Bad	0.482
0.75	Very bad	1
<Disutility>		0.85525

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.2	Bad	0.482
0.75	Very bad	1
<Disutility>		0.85525

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.2	Bad	0.482
0.75	Very bad	1
<Disutility>		0.85525

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.2	Bad	0.482
0.75	Very bad	1
<Disutility>		0.85525

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.2	Bad	0.482
0.75	Very bad	1
<Disutility>		0.85525

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.04	Weak	0.2
0.2	Bad	0.482
0.75	Very bad	1
<Disutility>		0.85525

Table 6.5-- Conditional Probabilities and Associated Disutilities of Stakeholder Reactions in case of Top Event Occurrence (Short-On)

SHORT-OFF

METI RELATIONSHIP

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.35	Weak	0.2
0.575	Bad	0.42
0.075	Very bad	1
<Disutility>		0.3865

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.05	Weak	0.2
0.65	Bad	0.42
0.3	Very bad	1
<Disutility>		0.583

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.35	Weak	0.2
0.575	Bad	0.42
0.075	Very bad	1
<Disutility>		0.3865

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.05	Weak	0.2
0.65	Bad	0.42
0.3	Very bad	1
<Disutility>		0.583

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.05	Weak	0.2
0.65	Bad	0.42
0.3	Very bad	1
<Disutility>		0.583

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.075
0.35	Weak	0.2
0.575	Bad	0.42
0.075	Very bad	1
<Disutility>		0.3865

LOCAL GOVERNMENT RELATIONSHIP

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.4	Weak	0.167
0.55	Bad	0.436
0.05	Very bad	1
<Disutility>		0.3566

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.05	Weak	0.167
0.4	Bad	0.436
0.55	Very bad	1
<Disutility>		0.73275

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.05	Weak	0.167
0.4	Bad	0.436
0.55	Very bad	1
<Disutility>		0.73275

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.05	Weak	0.167
0.2	Bad	0.436
0.75	Very bad	1
<Disutility>		0.84555

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.05	Weak	0.167
0.4	Bad	0.436
0.55	Very bad	1
<Disutility>		0.73275

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0	Good	0.041
0.4	Weak	0.167
0.55	Bad	0.436
0.05	Very bad	1
<Disutility>		0.3566

EFFECT ON MEDIA COVERAGE

TOP EVENT 1 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.2	Weak	0.2
0.75	Bad	0.482
0.04	Very bad	1
<Disutility>		0.44235

TOP EVENT 2 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.2	Weak	0.2
0.75	Bad	0.482
0.04	Very bad	1
<Disutility>		0.44235

TOP EVENT 3 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.2	Weak	0.2
0.75	Bad	0.482
0.04	Very bad	1
<Disutility>		0.44235

TOP EVENT 4 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.2	Weak	0.2
0.75	Bad	0.482
0.04	Very bad	1
<Disutility>		0.44235

TOP EVENT 5 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.2	Weak	0.2
0.75	Bad	0.482
0.04	Very bad	1
<Disutility>		0.44235

TOP EVENT 6 OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.01	Good	0.085
0.2	Weak	0.2
0.75	Bad	0.482
0.04	Very bad	1
<Disutility>		0.44235

Table 6.6—Conditional Probabilities and Associated Disutilities of Stakeholder Reactions in Case of Top Event Occurrence (Short-Off)

LONG-ON

METI RELATIONSHIP

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.2	Very good	0
0.75	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.06625

LOCAL GOVERNMENT RELATIONSHIP

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.75	Very good	0
0.2	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.025

EFFECT ON MEDIA COVERAGE

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.2	Very good	0
0.75	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.06625

LONG-OFF

METI RELATIONSHIP

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.2	Very good	0
0.75	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.06625

LOCAL GOVERNMENT RELATIONSHIP

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.2	Very good	0
0.75	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.06625

EFFECT ON MEDIA COVERAGE

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.2	Very good	0
0.75	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.06625

Table 6.7—Conditional Probabilities and Associated Disutilities of Stakeholder Reactions in case of Top Event Occurrence (Long Outage)

SHORT-ON

METI RELATIONSHIP

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.75	Very good	0
0.2	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.025

LOCAL GOVERNMENT RELATIONSHIP

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.75	Very good	0
0.2	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.025

EFFECT ON MEDIA COVERAGE

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.75	Very good	0
0.2	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.025

SHORT-OFF

METI RELATIONSHIP

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.2	Very good	0
0.75	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.06625

LOCAL GOVERNMENT RELATIONSHIP

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0	Very good	0
0.2	Good	0.075
0.75	Weak	0.2
0.05	Bad	0.42
0	Very bad	1
<Disutility>		0.186

EFFECT ON MEDIA COVERAGE

NO TOP EVENT OCCURRING

P(SI/T)	Scale	Disutility
0.2	Very good	0
0.75	Good	0.075
0.05	Weak	0.2
0	Bad	0.42
0	Very bad	1
<Disutility>		0.06625

Table 6.8—Conditional Probabilities and Associated Disutilities of Stakeholder Relations in case of No Top Event Occurrence (Short Outage)

CORRESPONDING DISUTILITIES FOR EACH PM

IN CASE OF TOP EVENT OCCURRING

DECISION OPTION	PC	WC	PU	COST	METI	LG	WL	MC
LONG-ON								
TE1	0	0	0.095	0	0.412	0.59175	0.0737	0.57035
TE2	0	0	0.095	0	0.434	0.4104	0.0737	0.57035
TE3	0	0	0.095	0	0.412	0.59175	0.0737	0.57035
TE4	0	0	0.095	0	0.434	0.4104	0.0737	0.57035
TE5	0	0	0.095	0	0.434	0.4104	0.0737	0.57035
TE6	0	0	0.095	0	0.412	0.59175	0.0737	0.57035
LONG-OFF	**PC**	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
TE1	0	0	0.095	0	0.34075	0.4386	0.315	0.28725
TE2	0	0	0.095	0	0.412	0.8039	0.315	0.28725
TE3	0	0	0.095	0	0.34075	0.4386	0.315	0.28725
TE4	0	0	0.095	0	0.412	0.8039	0.315	0.28725
TE5	0	0	0.095	0	0.412	0.8039	0.315	0.28725
TE6	0	0	0.095	0	0.34075	0.4386	0.315	0.28725

CORRESPONDING DISUTILITIES FOR EACH PM

IN CASE OF NO TOP EVENT OCCURRING

DECISION OPTION	PC	WC	PU	COST	METI	LG	WL	MC
LONG-ON	0	0	0.0702	0	0.06625	0.025	0.0742	0.06625
LONG-OFF	0	0	0.0702	0	0.06625	0.06625	1	0.06625

Table 6.10—Corresponding Disutilities (Long Outage Case)

CORRESPONDING DISUTILITIES
IN CASE OF TOP EVENT OCCURRING

DECISION OPTION	PC	WC	PU	COST	METI	LG	WL	MC
SHORT-ON	**PC**	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
TE1	0	0	0.061	0	0.583	0.4117	0	0.85525
TE2	0	0	0.061	0	0.405	0.4386	0	0.85525
TE3	0	0	0.061	0	0.583	0.4386	0	0.85525
TE4	0	0	0.061	0	0.405	0.4104	0	0.85525
TE5	0	0	0.061	0	0.405	0.4386	0	0.85525
TE6	0	0	0.061	0	0.583	0.4117	0	0.85525
SHORT-OFF	**PC**	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
TE1	0	0	0.061	0	0.3865	0.3566	0.042	0.44235
TE2	0	0	0.061	0	0.583	0.73275	0.042	0.44235
TE3	0	0	0.061	0	0.3865	0.73275	0.042	0.44235
TE4	0	0	0.061	0	0.583	0.84555	0.042	0.44235
TE5	0	0	0.061	0	0.583	0.73275	0.042	0.44235
TE6	0	0	0.061	0	0.3865	0.3566	0.042	0.44235

CORRESPONDING DISUTILITIES
IN CASE OF NO TOP EVENT OCCURRING

DECISION OPTION	PC	WC	PU	COST	METI	LG	WL	MC
SHORT-ON	0	0	0.0536	0	0.025	0.025	0.015	0.025
SHORT-OFF	0	0	0.0536	0	0.06625	0.186	0.0737	0.06625

Table 6.11—Corresponding Disutilities (Short Outage Case)

DISUTILITY*FREQUENCY (EXPECTED DISUTILITY)
IN CASE OF TOP EVENT OCCURRING

DECISION OPTION

LONG-ON	PC	WC	PU	COST	METI	LG	WL	MC
TE1	0.00E+00	0.00E+00	7.83E-04	0.00E+00	3.39E-03	4.88E-03	6.07E-04	4.70E-03
TE2	0.00E+00	0.00E+00	3.40E-06	0.00E+00	1.56E-05	1.47E-05	2.64E-06	2.04E-05
TE3	0.00E+00	0.00E+00	1.49E-04	0.00E+00	6.45E-04	9.26E-04	1.15E-04	8.93E-04
TE4	0.00E+00	0.00E+00	1.48E-21	0.00E+00	6.76E-21	6.39E-21	1.15E-21	8.88E-21
TE5	0.00E+00	0.00E+00	7.05E-04	0.00E+00	3.22E-03	3.05E-03	5.47E-04	4.23E-03
TE6	0.00E+00	0.00E+00	4.08E-04	0.00E+00	1.77E-03	2.54E-03	3.16E-04	2.45E-03
SUM	**0.00E+00**	**0**	**2.05E-03**	**0**	**9.04E-03**	**0.0114013**	**0.0015884**	**0.0122923**
LONG-OFF	**PC**	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
TE1	0	0	0.000782794	0.00E+00	2.81E-03	3.61E-03	0.0025956	2.37E-03
TE2	0	0	3.40435E-06	0.00E+00	1.48E-05	2.88E-05	1.129E-05	1.03E-05
TE3	0	0	0.000148709	0.00E+00	5.33E-04	6.87E-04	0.0004931	4.50E-04
TE4	0	0	1.47932E-21	0.00E+00	6.42E-21	1.25E-20	4.905E-21	4.47E-21
TE5	0	0	0.000704971	0.00E+00	3.06E-03	5.97E-03	0.0023375	2.13E-03
TE6	0	0	0.000407587	0.00E+00	1.46E-03	1.88E-03	0.0013515	1.23E-03
SUM	**0**	**0**	**0.002047465**	**0**	**0.0078752**	**0.0121767**	**0.006789**	**0.0061909**

DISUTILITY*FREQUENCY
IN CASE OF NO TOP EVENT OCCURRING

DECISION OPTION	PC	WC	PU	COST	METI	LG	WL	MC
LONG-ON	0	0	0.0702	0	0.06625	0.025	0.0742	0.06625
LONG-OFF	0	0	0.0702	0	0.06625	0.06625	1	0.06625

Table 6.12—Expected Disutilities (Long Outage Case)

DISUTILITY*FREQUENCY (EXPECTED DISUTILITY)

IN CASE OF TOP EVENT OCCURRING

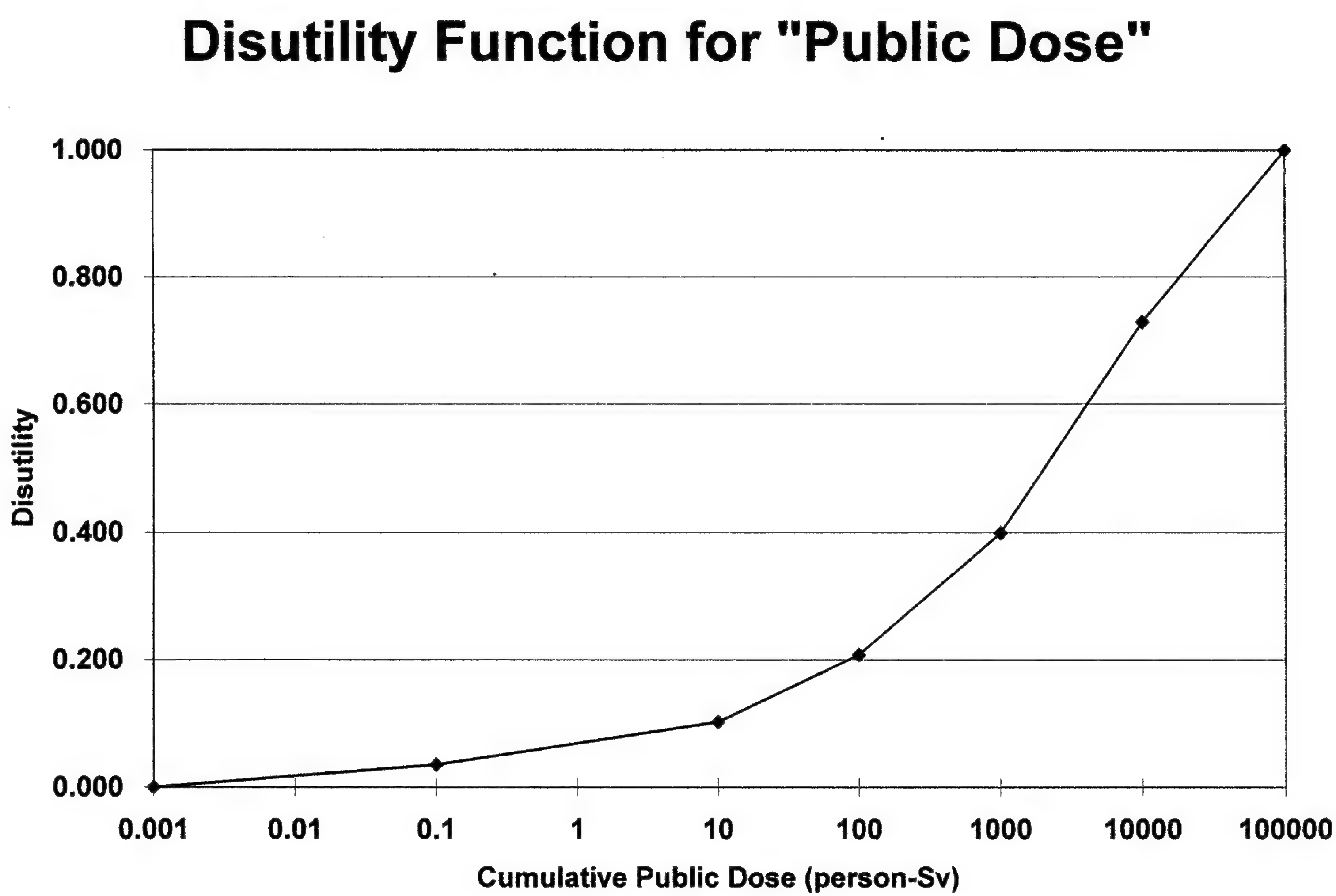
DECISION OPTION: SHORT-ON	PC	WC	PU	COST	METI	LG	WL	MC
TE1	0.00E+00	0.00E+00	5.03E-04	0.00E+00	4.80E-03	3.39E-03	0.00E+00	7.05E-03
TE2	0.00E+00	0.00E+00	2.19E-06	0.00E+00	1.45E-05	1.57E-05	0.00E+00	3.06E-05
TE3	0.00E+00	0.00E+00	9.55E-05	0.00E+00	9.13E-04	6.87E-04	0.00E+00	1.34E-03
TE4	0.00E+00	0.00E+00	9.50E-22	0.00E+00	6.31E-21	6.39E-21	0.00E+00	1.33E-20
TE5	0.00E+00	0.00E+00	4.53E-04	0.00E+00	3.01E-03	3.25E-03	0.00E+00	6.35E-03
TE6	0.00E+00	0.00E+00	2.62E-04	0.00E+00	2.50E-03	1.77E-03	0.00E+00	3.67E-03
SUM	0	0	0.001315	0	0.011238	0.009116	0	0.018433
SHORT-OFF	**PC**	**WC**	**PU**	**COST**	**METI**	**LG**	**WL**	**MC**
TE1	0.00E+00	0.00E+00	6.03E-04	0.00E+00	3.82E-03	3.53E-03	4.15E-04	4.38E-03
TE2	0.00E+00	0.00E+00	3.62E-06	0.00E+00	3.46E-05	4.34E-05	2.49E-06	2.62E-05
TE3	0.00E+00	0.00E+00	1.43E-04	0.00E+00	9.09E-04	1.72E-03	9.88E-05	1.04E-03
TE4	0.00E+00	0.00E+00	2.28E-21	0.00E+00	2.18E-20	3.16E-20	1.57E-21	1.65E-20
TE5	0.00E+00	0.00E+00	5.73E-04	0.00E+00	5.48E-03	6.88E-03	3.94E-04	4.15E-03
TE6	0.00E+00	0.00E+00	3.81E-04	0.00E+00	2.41E-03	2.23E-03	2.62E-04	2.76E-03
SUM	0	0	0.001704	0	0.012656	0.014403	0.001173	0.012359

DISUTILITY*FREQUENCY

IN CASE OF NO TOP EVENT OCCURRING

DECISION OPTION	PC	WC	PU	COST	METI	LG	WL	MC
SHORT-ON	0	0	0.0536	0	0.025	0.025	0.015	0.025
SHORT-OFF	0	0	0.0536	0	0.06625	0.186	0.0737	0.06625

Table 6.13—Expected Disutilities (Short-Outage Case)



* Figure 6.2—Disutility Function for Public Casualty (PC) [25]

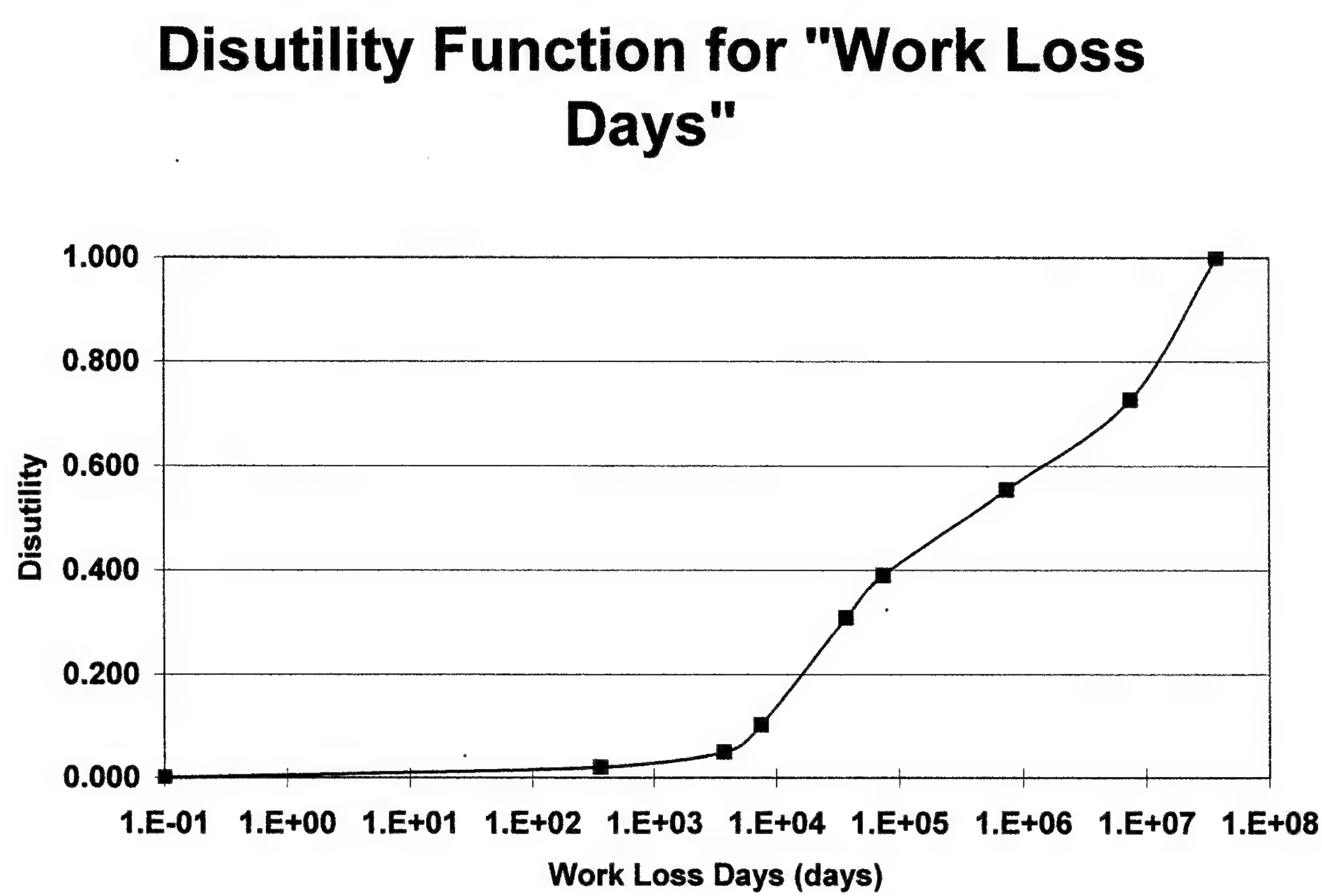


Figure 6.3—Disutility Function for Worker Casualty (WC) [25]

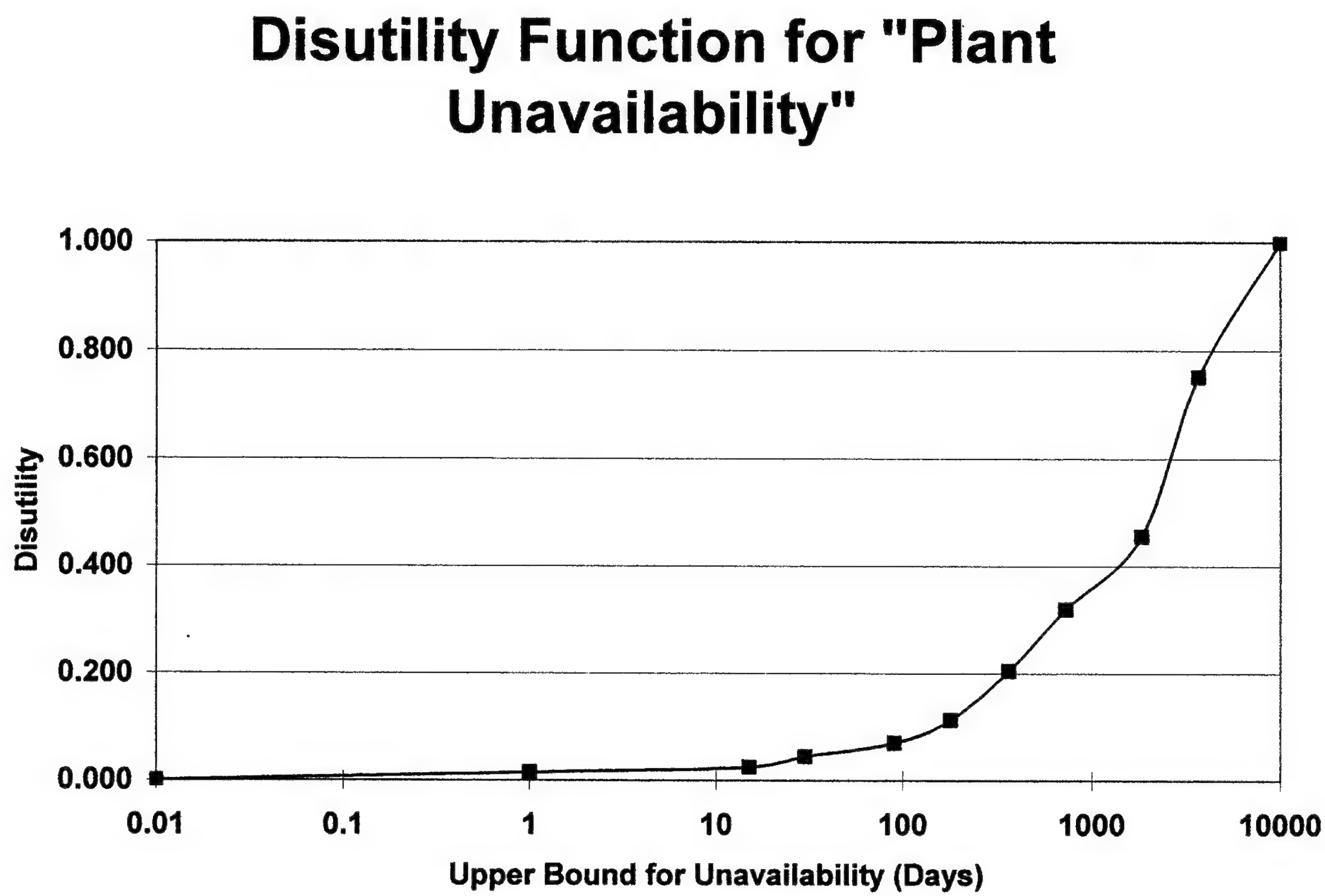


Figure 6.4—Disutility Function for Plant Unavailability (PU) [25]

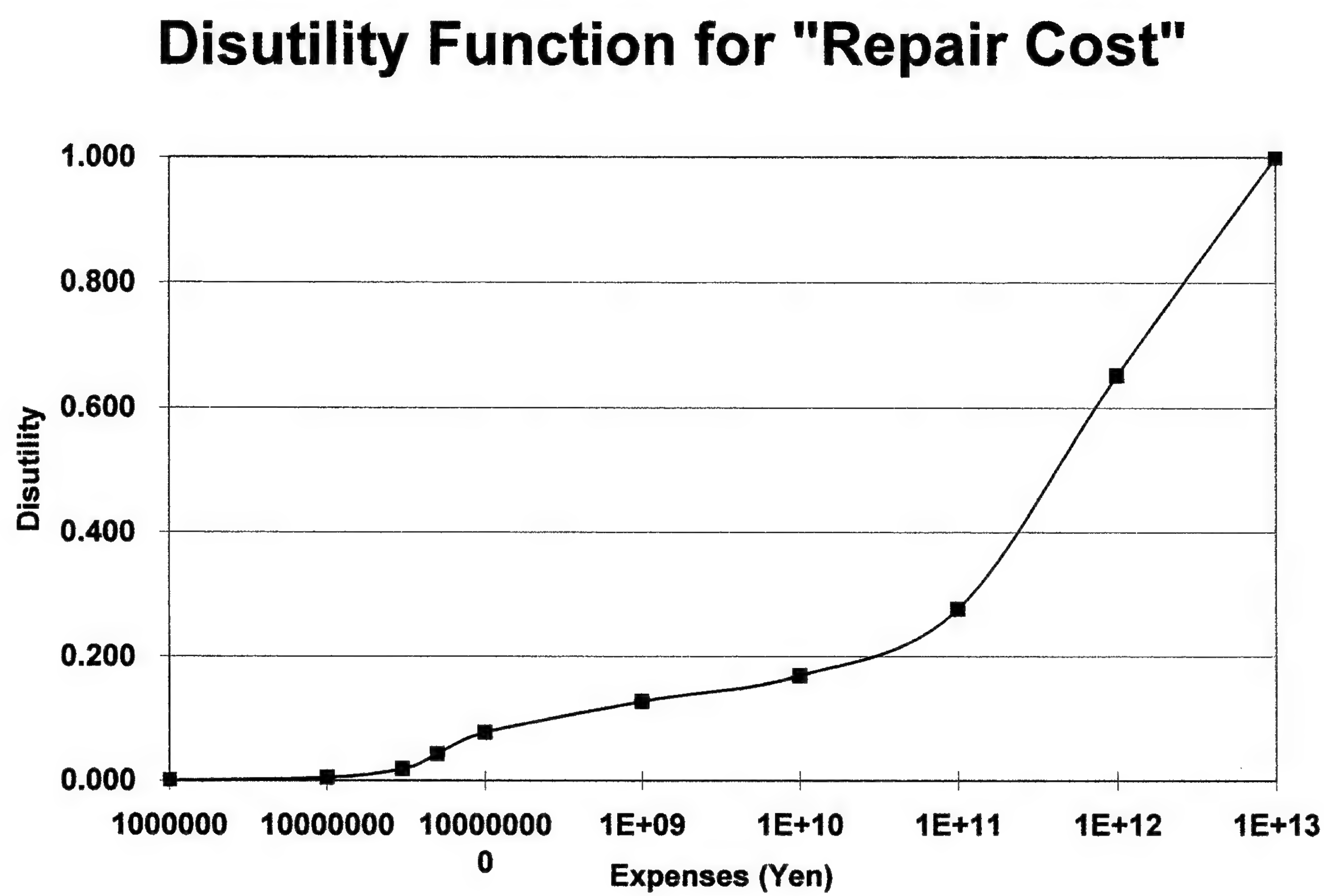
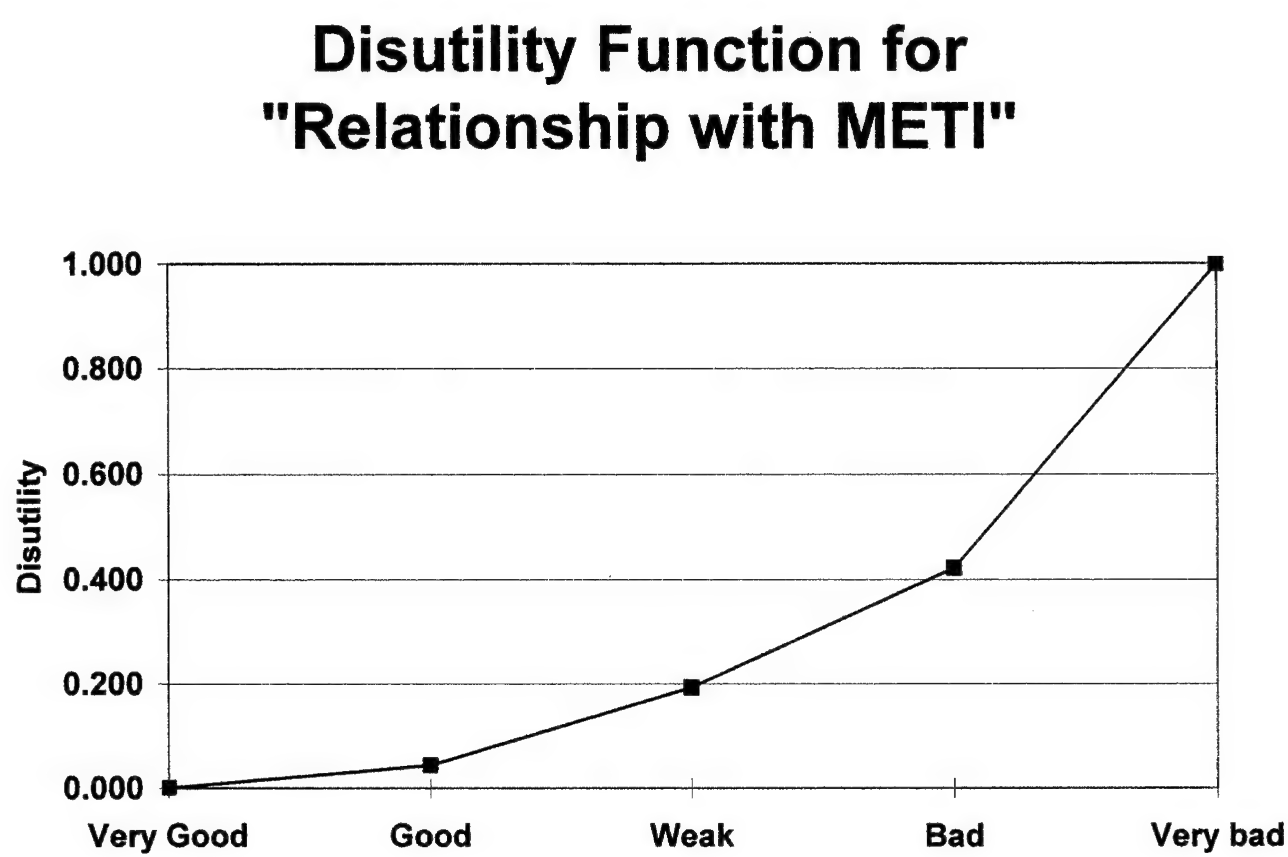


Figure 6.5—Disutility Function for Repair Cost (Cost) [25]



'Figure 6.6—Disutility Function for "Relationship with METI"

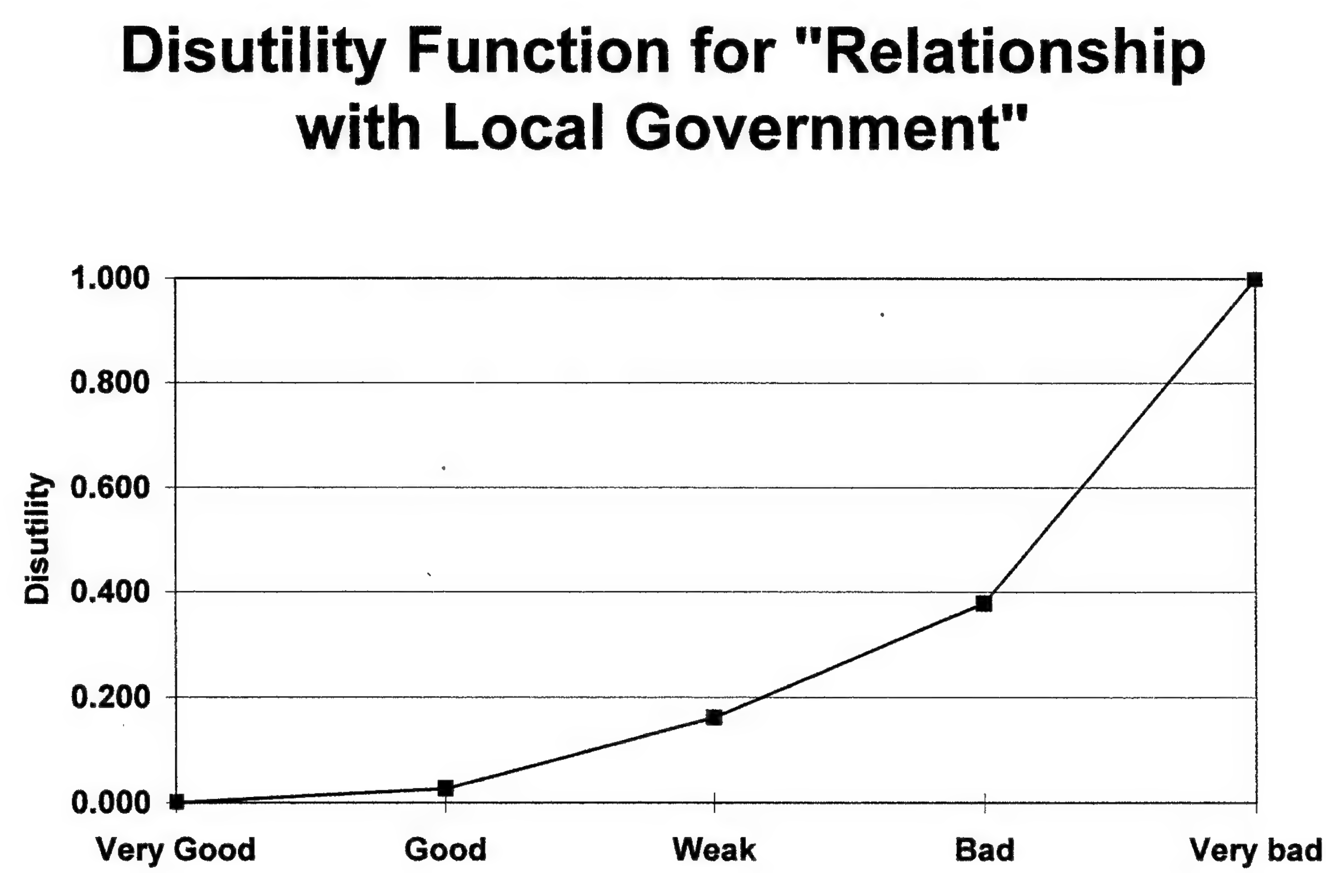


Figure 6.7—Disutility Function for "Relationship with Local Government"

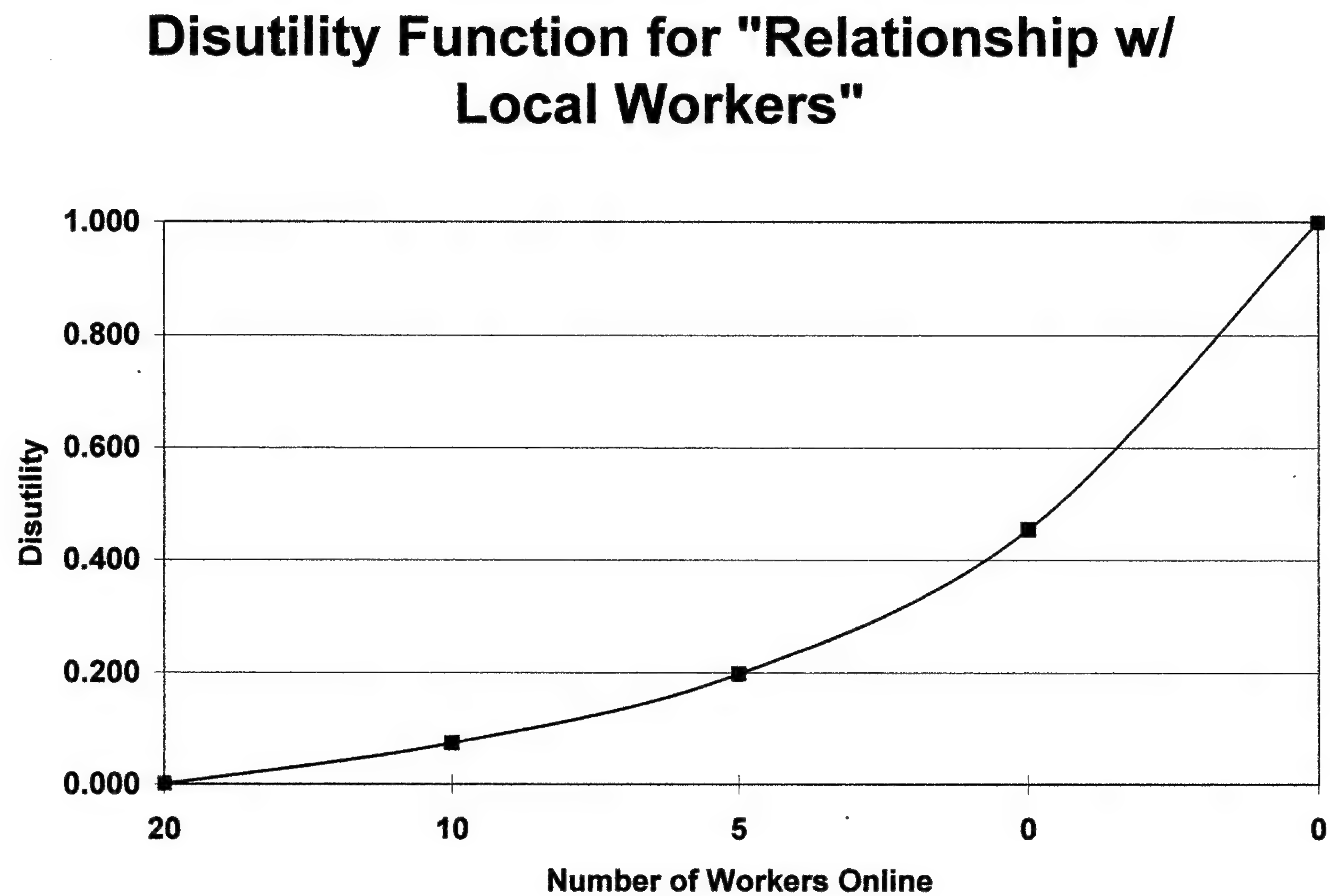


Figure 6.8—Disutility Function for "Relationship with Local Workers"

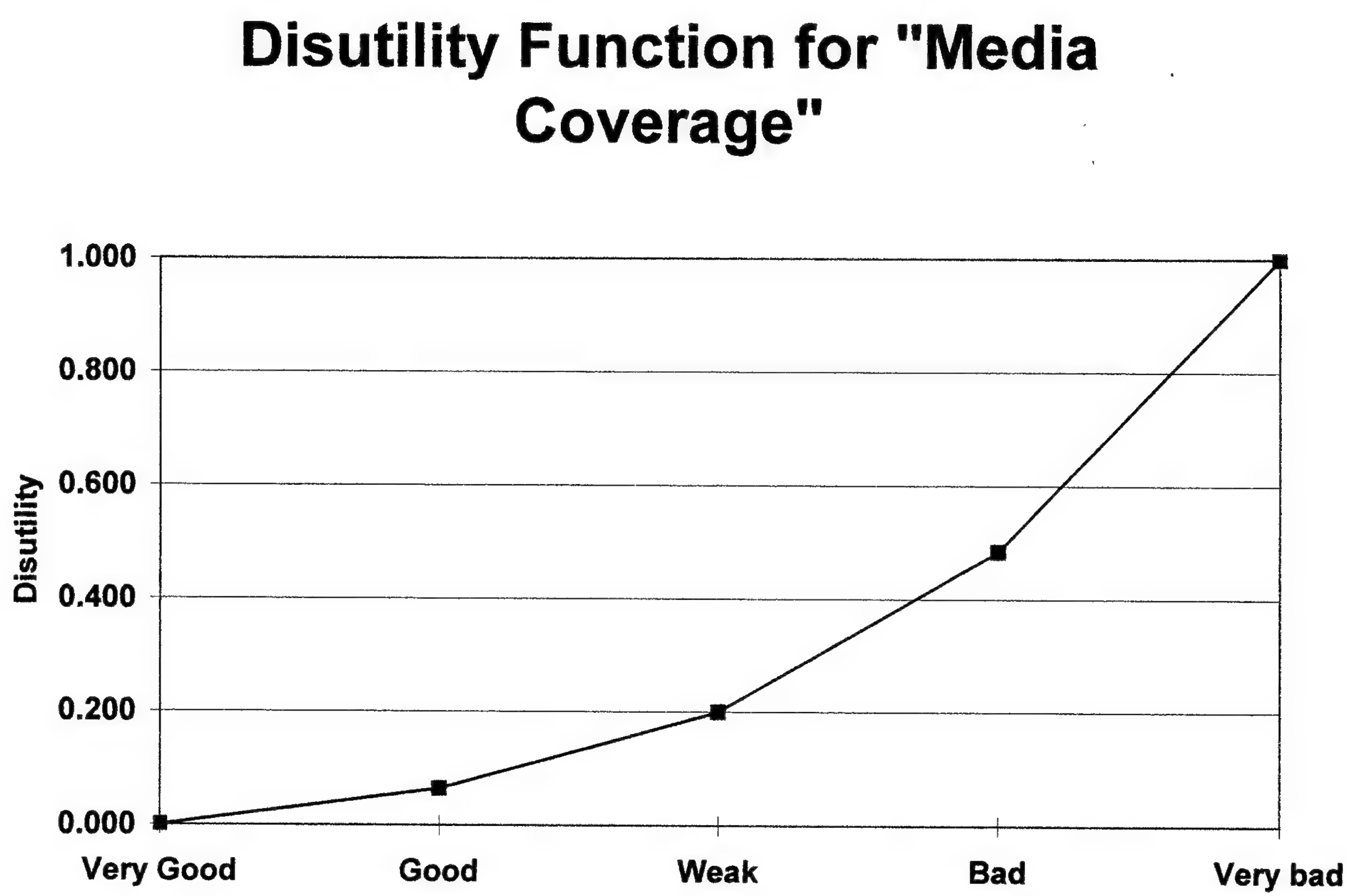


Figure 6.9—Disutility Function for Media Coverage (MC) [25]

Interpretation of Results

7.1 Introduction

Using HCU maintenance as a case study for application of Multi-Attribute Utility Theory, the following decision options were considered for TEPCO:

Long-On: On-line HCU maintenance with no change in outage duration
Long-Off: Off-line HCU maintenance with no change in outage duration
Short-On: On-line HCU maintenance with a shortened outage
Short-Off: Off-line HCU maintenance with a shortened outage

Because no failure data were available from TEPCO, we utilized NPRDS failure data from four US BWR plants: Brunswick1, Peach Bottom 3, Quad Cities 1, and Susquehanna 1. The method of analysis described in Section 6 was used to calculate the overall performance index for each decision option and considers both the occurrence and non-occurrence of an HCU top event.

7.2 Results

Figure 7.1 shows the overall performance index profile for the Brunswick 1 NPS, considering various importance weightings of performance measure categories and occurrence and non-occurrence of system failure. The order of preference for the decision options is 1) Short-On, 2) Long-On, 3) Short-Off, and 4) Long-Off; except for the 45/45/10 distribution where the order of preference is 1) Short-On, 2) Short-Off, 3) Long-On, and 4) Long-Off.

7.3 Interpretation of Results

7.3.1 Ranking of Options

A use of the AHP is obtaining the rank order of attractiveness of the decision options. The results of this study indicate that the current practice ("Long-Off") of performing HCU maintenance off-line during Japan's long outage durations is the least preferred option. Based upon the analysis results shown in Figure 7.1, the best option is "Short-On" (On-line HCU maintenance with a shortened outage) and the worst option is "Long-Off" (Off-line HCU maintenance with a long outage).

The "Long-On" and "Short-Off" options can interchange ranking based upon the weighting of decision maker preference to safety, economics, and stakeholder relations [as seen in 45/45/10 where the ranking is 1) Short-On, 2) Short-Off, 3) Long-On, 4) Long-Off]. The "Performance Index Value" axis on the graph represents the overall performance index calculated for each decision option. The "Weighting" axis represents the various weights considered to reflect the decision maker's preferences toward safety, economics, and stakeholder relations. For example, for the 50/25/25 weighting, the decision maker places 50% of the importance to safety, 25% to economics, and 25% to stakeholder relations.

The major factors affecting the overall performance index value are shown in Figure 7.2 and Figure 7.3, where we considered the weighting of 50% to safety, 25% to economics, and 25% to stakeholders. The column heights represent the utility multiplied by the assigned weight for the performance measure. Thus the height of the column is directly proportional to the level of disfavor (i.e. disutility) with regard to the given performance measure. Looking at Figure 7.2 and considering each performance measure individually, the most favorable decision option is as follows:

1. **PU**: Short-On, indicating that this decision option yields the lowest plant unavailability.
2. **METI and MC**: Long-Off, indicating that the relationship with METI and the media is best when the current HCU maintenance practice is maintained.
3. **LG and WL**: Short-On, indicating that the local government and local community are pleased when workers are employed year round.

7.3.2 Identification of Factors that Can Improve a Decision Option's Attractiveness

A valuable use of MAUT is the identification of the performance metrics which would be valuable to improve in rendering a particular decision option more attractive. The cases of both occurrence and avoidance of system failures (Figure 7.4) are considered and the combination of both yields a chart similar to Figure 7.3. Consequently, Figure 7.3 can be used exclusively to determine the major factors affecting the overall performance index. It can be seen that stakeholder relations (METI, LG, WL, and MC) and plant unavailability are the major contributors to the overall performance index, with "Worker Load" and "Plant Unavailability" playing the most significant roles in establishing the "Long-Off" option as the most unfavorable.

Knowing that "Worker Load" and "Plant Unavailability" are responsible for the high performance index of the "Long-Off" option, the utilities can make the "Long-Off"option more attractive by making efforts to improve the "Worker Load" and "Plant Unavailability." Figure 7.2 is a good representation of how MAUT can be used to understand better how the individual performance measures are impacted by the decision options available. This knowledge allows the decision maker to identify the areas in which a decision option can be improved. For example, referring to Figure 4, the "Short-On" decision option can be made more attractive by making improvements in "Relations with METI" and "Media Coverage." The improvements in these two areas would lower

the overall performance index of the option, making it more attractive to the decision makers and stakeholders.

As mentioned earlier, "Long-On" and "Short-Off" can interchange ranking based on the weighting of decision maker preferences to safety, economics, and stakeholder relations. Figures 7.5 and 7.6 demonstrate how this occurs when we consider the weightings 50/25/25 and 45/45/10. As can be seen from this Figure 7.5, stakeholder relations play a significant role in differentiating between "Long-On" and "Short-Off." In the 50/25/25 case, "Long-On" is the preferred option over "Short-Off". However, in the 45/45/10 case, Plant Unavailability has the dominant effect on the overall performance index. Consequently, "Short-Off" is the preferred option over "Long-On" in Figure 7.6.

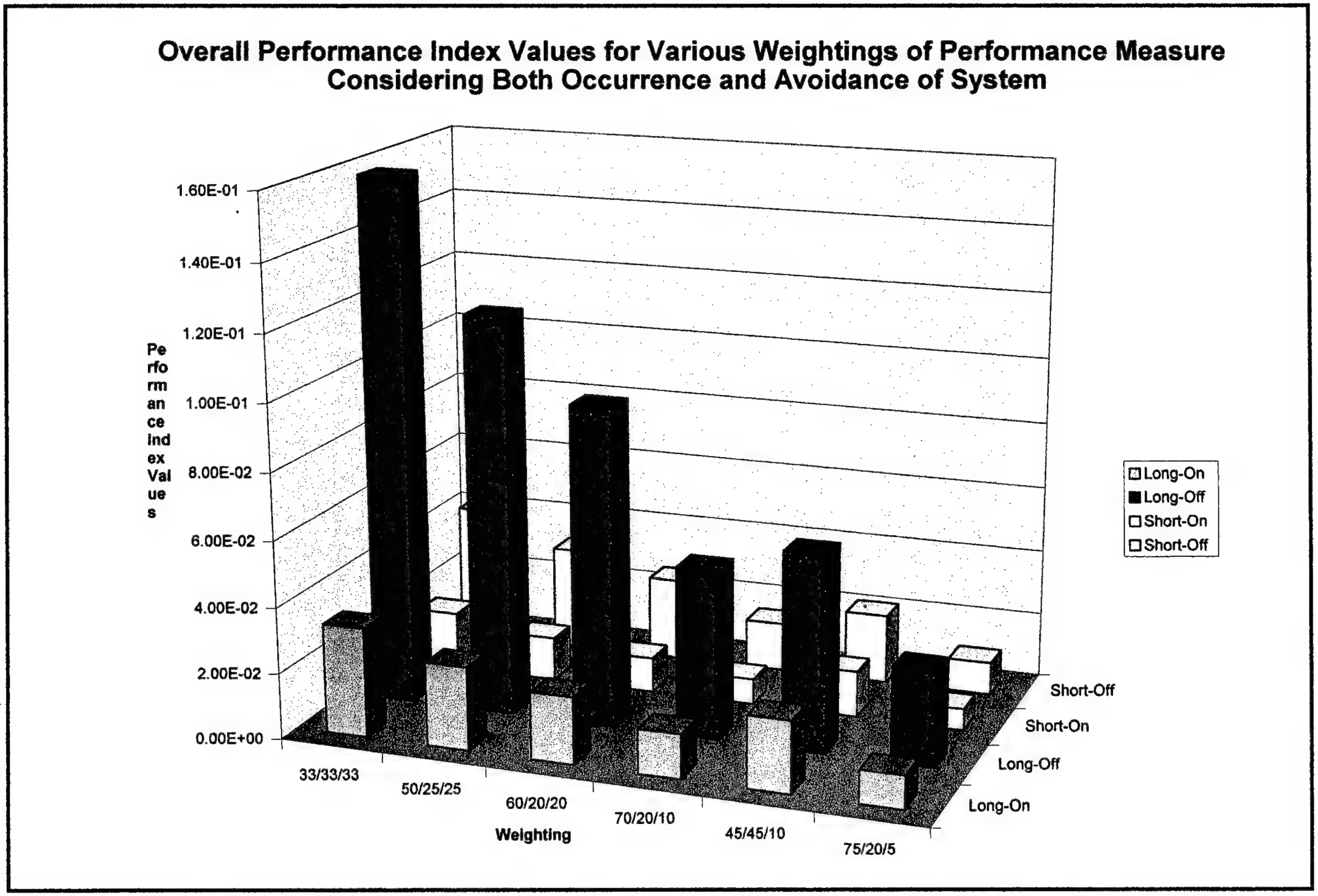


Figure 7.1—Overall Performance Index Values for Various Weightings of Performance Measure Categories (Brunswick 1)

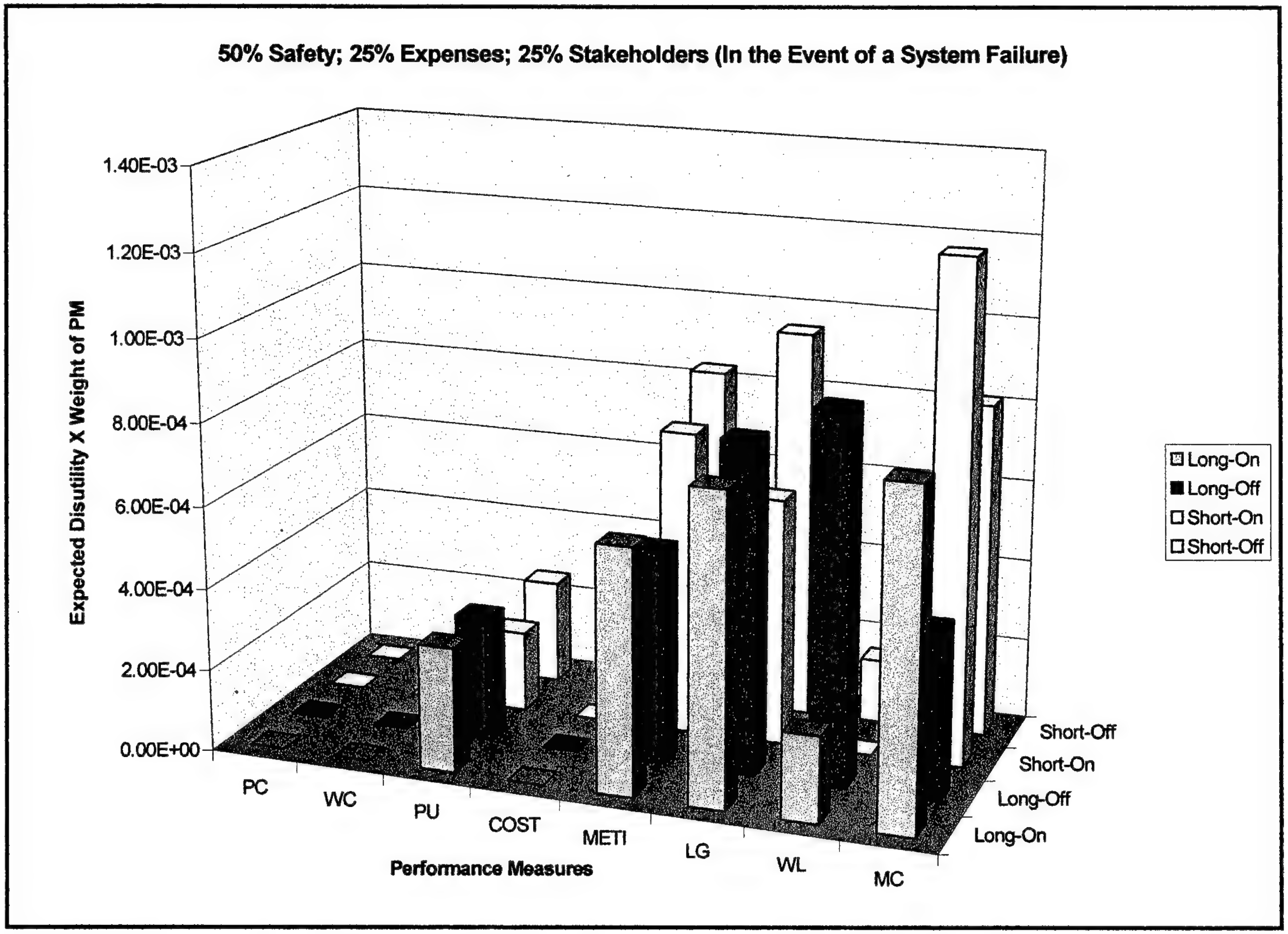


Figure 7.2-- Contributions to Overall Performance Index In Event of System Failure

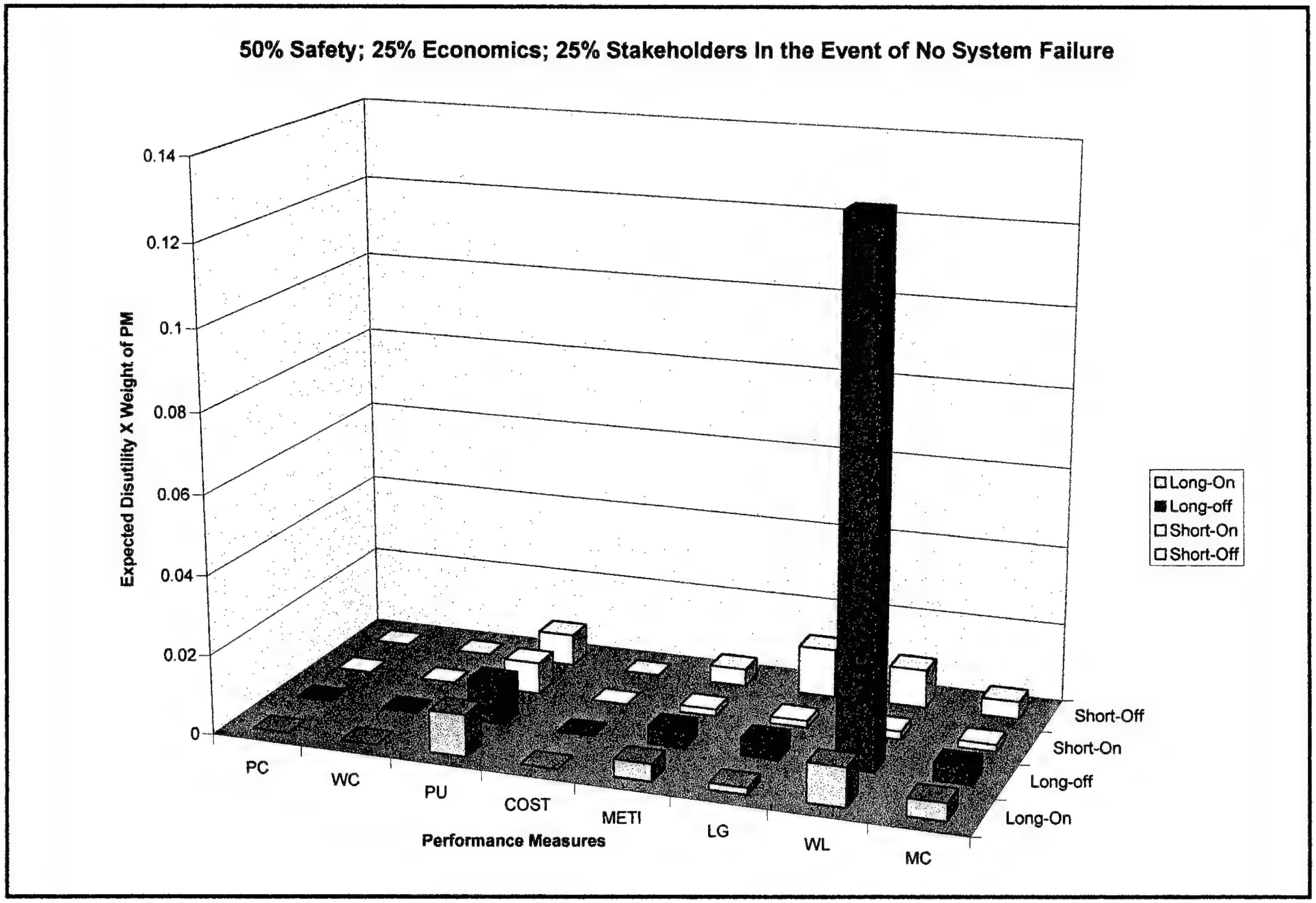


Figure 7.3-- Contributions to Overall Performance Index In Event of No System Failure

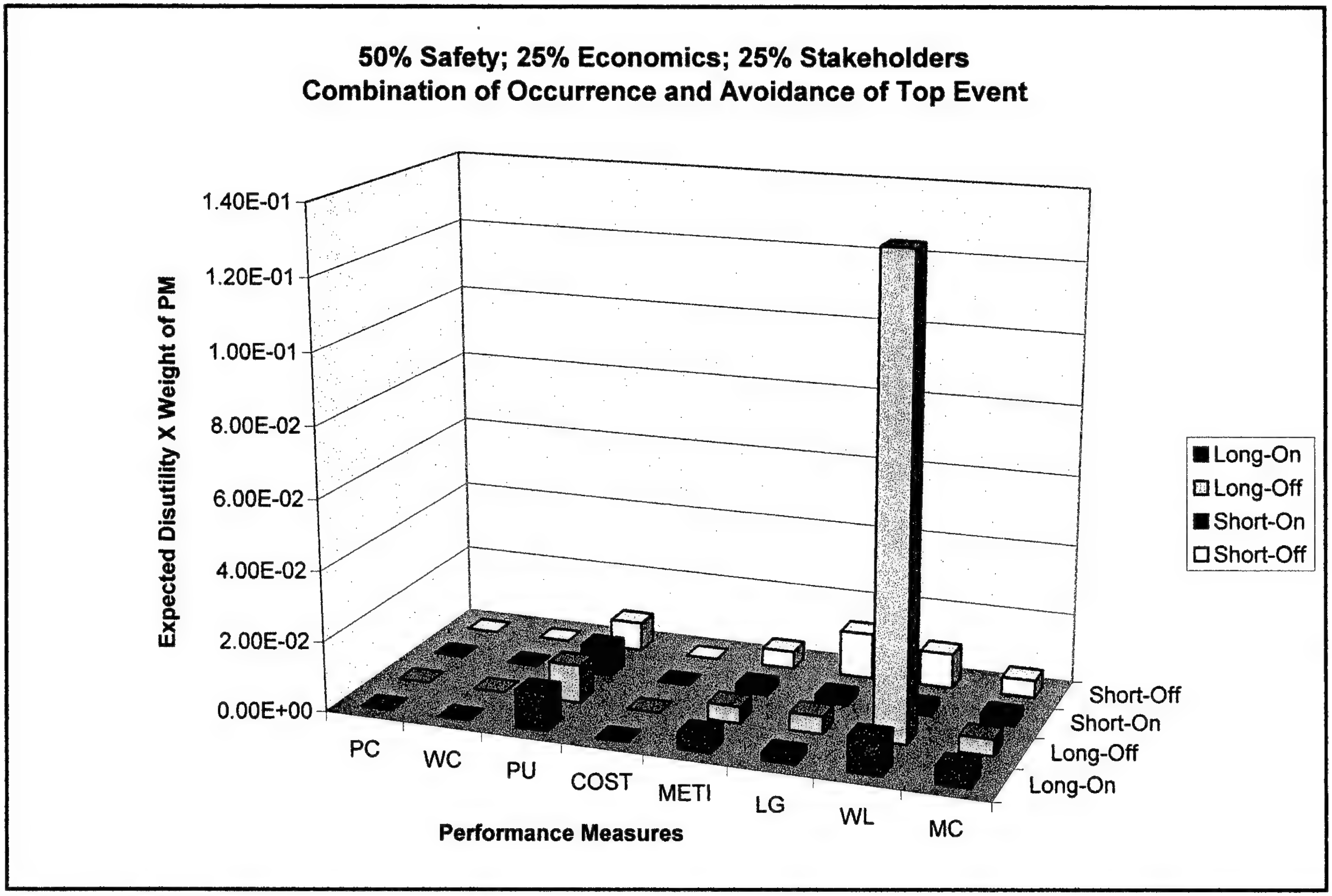


Figure 7.4—Total Contributions to Overall Performance Index Probability-Weighted (Combination of Occurrence and Avoidance of System Failure)

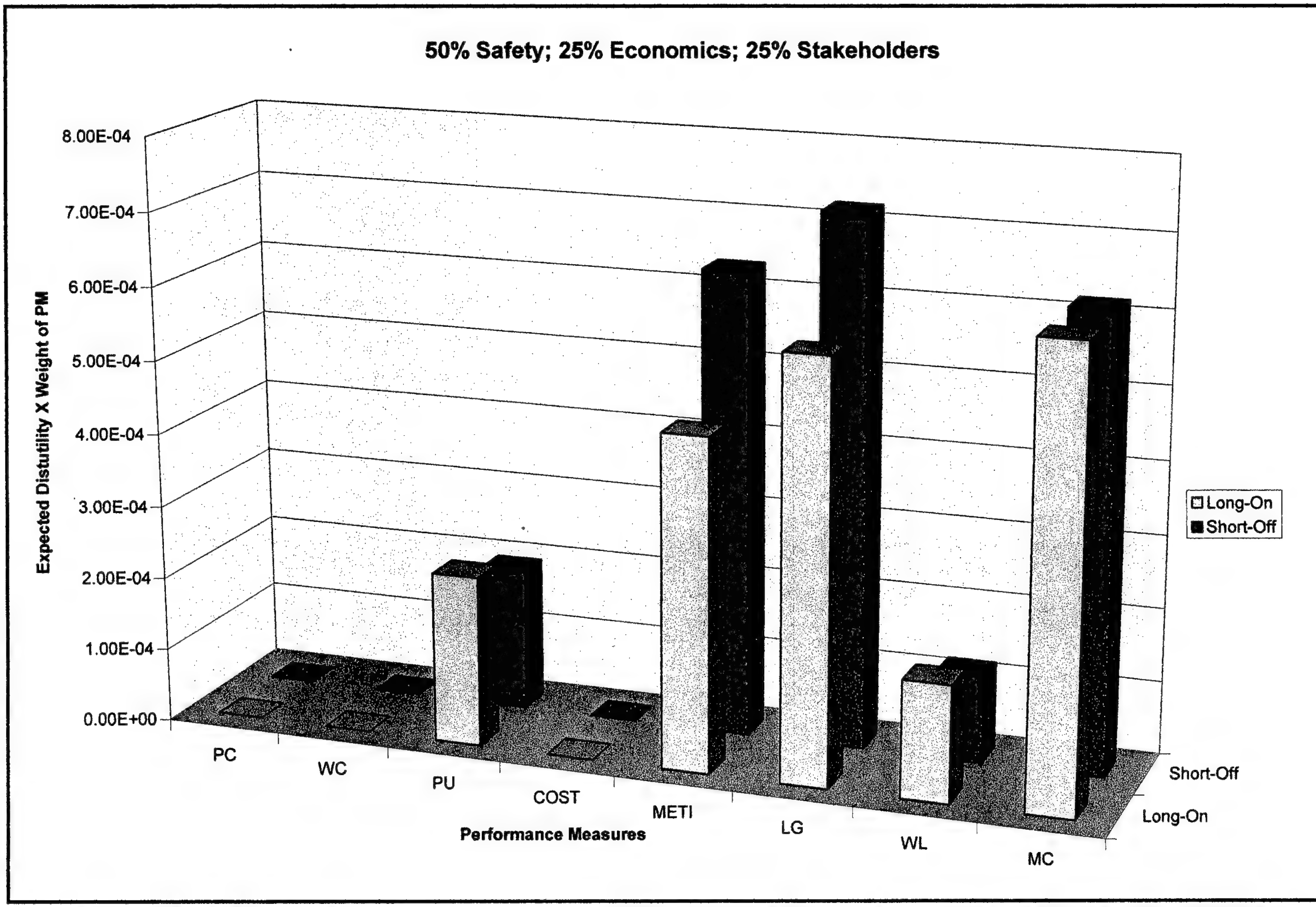


Figure 7.5—Influence of Stakeholder Relations in Differentiating Between "Long-On" and "Short-Off" (50/25/25)

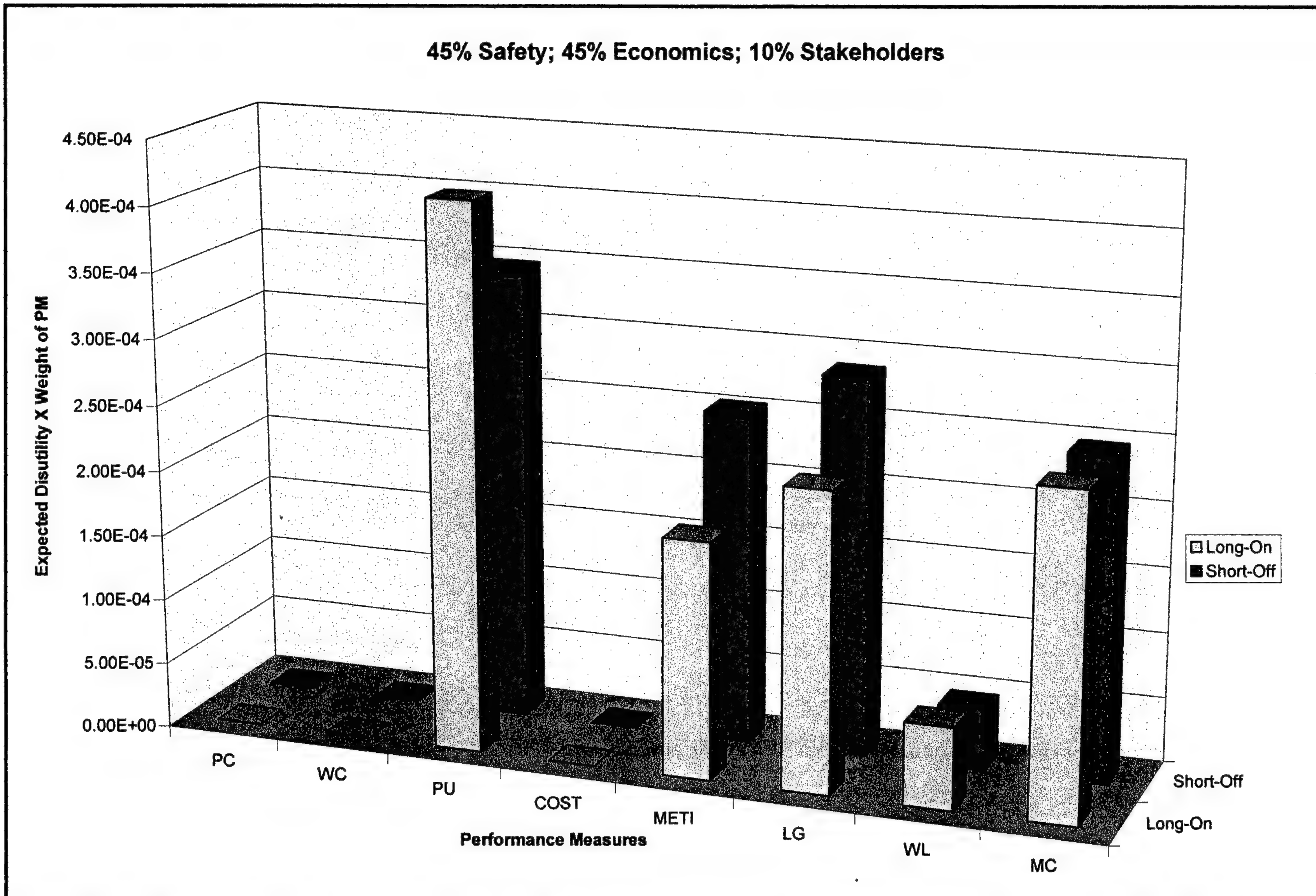


Figure 7.6—Influence of Plant Unavailability in Differentiating between "Long-On" Versus "Short-Off" (45/45/10)

Concluding Remarks

8.1 Summary of Results

By switching to on-line HCU maintenance, US plants have 1) managed to shorten plant outage durations, 2) lowered costs associated with refueling maintenance, 3) allowed more resources to be devoted to critical path items during refueling, and 4) employed more in-house plant personnel in the performance of HCU maintenance. Although this decision has produced significant benefits to the utilities, the decision to shift on-line was based solely upon a deterministic analysis, using expert judgment and ensuring compliance with the Technical Specifications.

With the use of Multi-Attribute Utility Theory, decision makers at TEPCO have a method by which they are able to carefully consider the HCU maintenance decision options available to them. This method allows them to tailor their preferences for safety, economics, and relations to stakeholders; and it provides a rank ordering of the desirability of each decision option. MAUT can be also be used to better understand how the individual performance measures are impacted by the decision options available. This knowledge allows the decision maker to identify the areas in which a decision option can be valuably improved.

The results of our study indicate that the current practice of performing HCU maintenance off-line during TEPCO's long outage durations is the least preferred option. Although the most preferred option is to perform HCU maintenance on-line during a shorter duration outage, this decision option is the most difficult to implement because the number of changes requiring management by the utility is greatest. These changes include shortening outage durations by shifting non-critical path maintenance items on-line, including HCU maintenance; and revamping its approach to critical path work by reducing the time required to complete critical path items.

More realistic alternatives are the “Long-On” and “Short-Off” options because the number of changes that a utility must implement are fewer than in the “Short-On” option. Either the “Long-On” or “Short-Off” option would be more likely to be accepted because either option would produce benefits consistent with the following goals:

1. To shorten the duration of outages.

2. To assure that maintenance takes place year-round, employing workers from the local community year-round, thus improving relations with the local government and public.

3. To enhance the competitiveness and safety of the nuclear power plants from the perspective of cost, using risk information.

8.2 Issues and Limitations

The analysis' results depend upon underlying assumptions regarding the data employed and each decision option's influence upon the performance measures. Consequently, these assumptions place some limitations on the precision of the calculated overall performance index value and the ranking of decision options.

First, the data gathered from the NPRDS database covering HCU failures are not comprehensive, and assumptions had to be made with regard to the frequency of occurrence of some basic events. In addition, the human error probability analysis depended upon the THERP and the modification factors obtained from Swain, et al. (1980) The human error probability estimates and performance shaping factors provided in Reference 22 were based upon the experience of the authors, and the calculated top event probabilities are based upon US utility data. As a result, the specific conditions at TEPCO were not accounted for in our study.

The analysis also employs a number of subjective judgments based on the expertise of a visiting TEPCO engineer. These judgments were used to estimate stakeholder reactions to the occurrence and non-occurrence of a top event, in light of the decision options being considered. In addition, subjective judgments were used to make assumptions regarding the effect of the decision options on the following performance measures: public casualty, worker casualty, repair cost, and plant unavailability. Clearly, these judgments need to be reviewed before making a serious evaluation of the decision options available for HCU maintenance. TEPCO decision makers must carefully consider their preferences with regard to safety, economics, and stakeholder relations and honestly evaluate the effect of the decision options on each performance measure.

8.3 Applications

This study, despite limitations presented by data and subjective judgments, provides a reasonable indication of the desirability of various HCU maintenance decision options. The use of MAUT allows the decision makers to consider not only safety and economics but also the impact on stakeholder relations. This formal analysis will 1) enhance consensus building, 2) provide a systematic method for processing a large amount of information, 3) provide formal rules for quantifying preferences, and 4) enhance the decision-making process by improving communication between decision makers. It is a valuable tool that can be applied to evaluate any decision option in light of the primary goals delineated by the decision makers.

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Appendix A: Fault Trees and Top Event Probability Data

This section contains complete fault trees for the top events considered for our study. The fault tree for Top Event 6 is omitted because it is almost identical to the fault tree for Top Event 5. Also included in this section are HCU failure data from four US Nuclear Power Plants: Brunswick 1, Peach Bottom 3, Quad Cities 1, and Susquehanna 1. These data were obtained from the Nuclear Plant Reliability Data System (NPRDS). All HCU basic events are listed along with their probabilities of occurrence (the method of calculation is presented in Section 4.5). The basic event probabilities are then used to calculate the top event probabilities (using Boolean algebra) that are utilized to find the overall performance index values for each decision option considered.

Notes: 1. Failure rates are in number of occurrences per year (#occurrences/yr).

2. "H"= Failures attributed to human error

3. Number of service failures equals number of times basic event occurred within report interval.

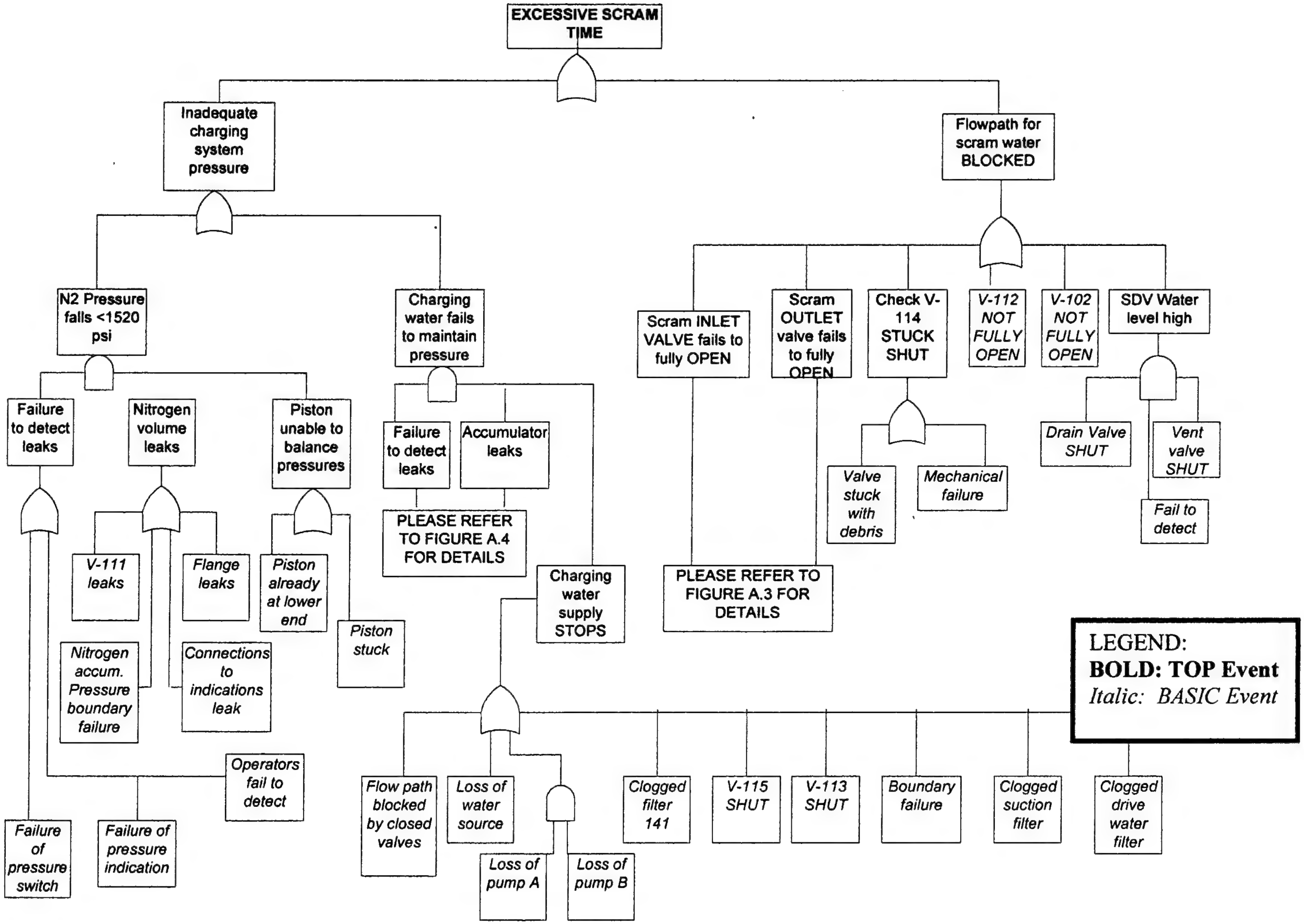

Figure A.1—Top Event 1 (Excessive Scram Time)

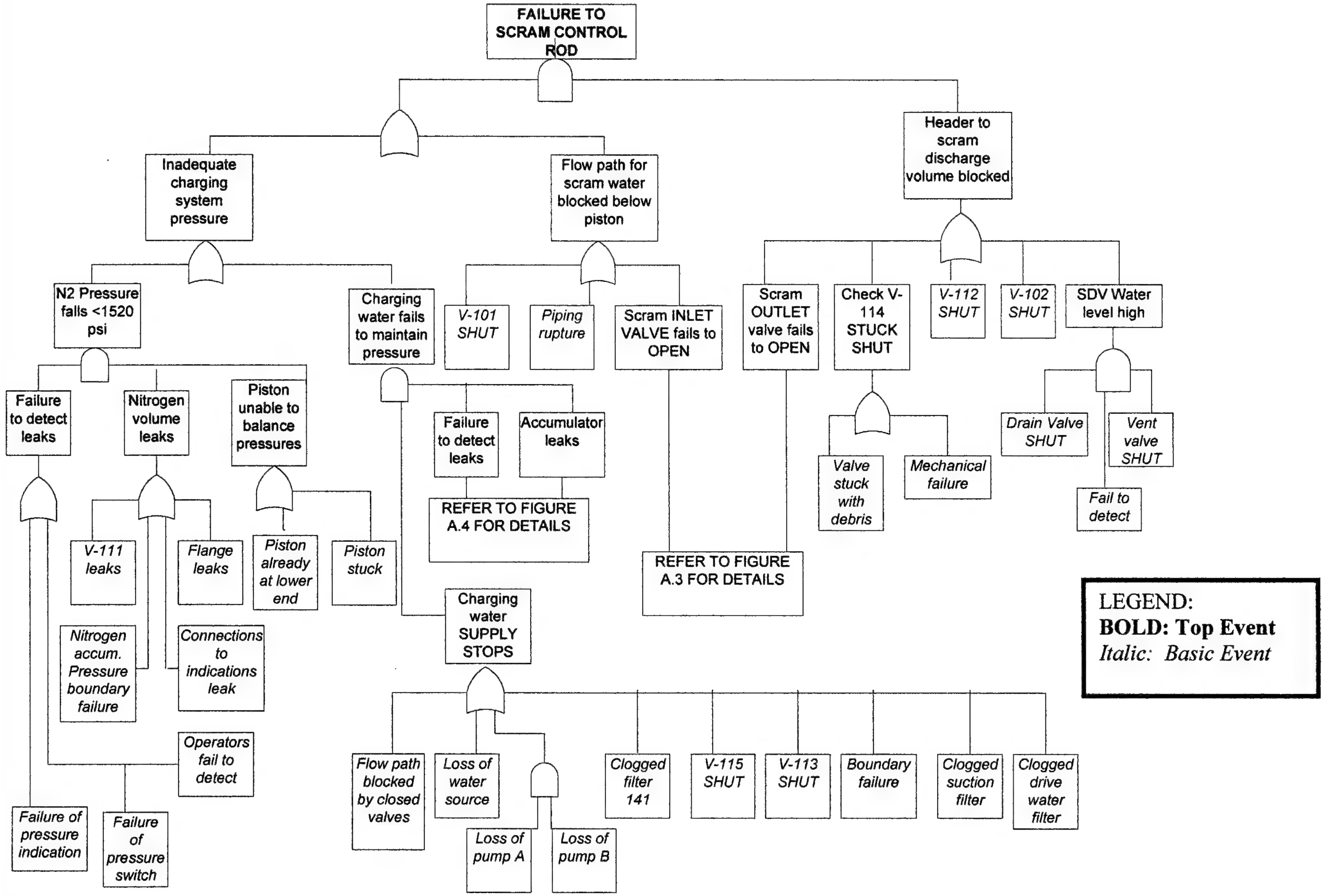

Figure A.2—Top Event 2 (Failure to Scram)

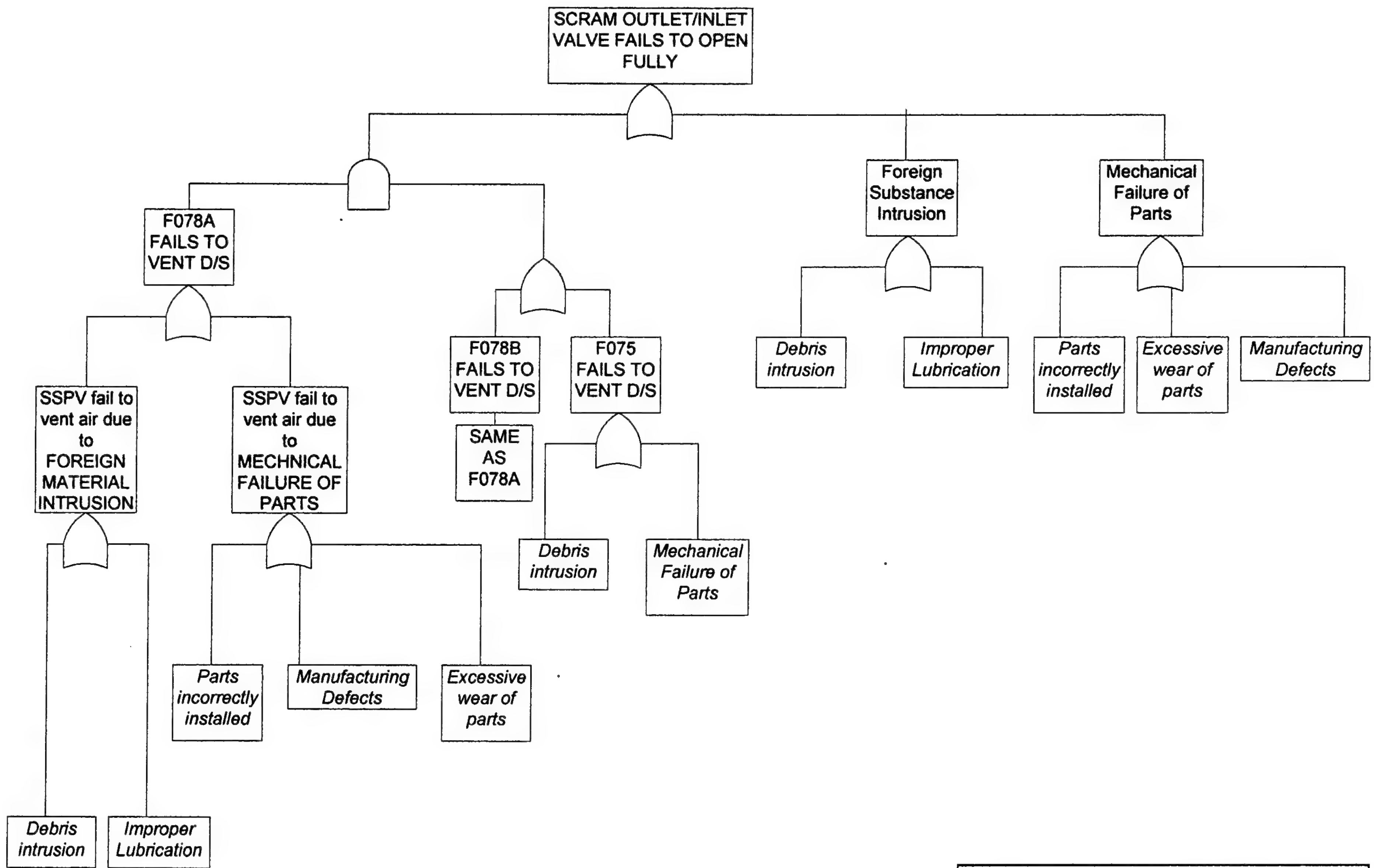

Figure A.3—Scram Outlet/Inlet Valve Failure to Open

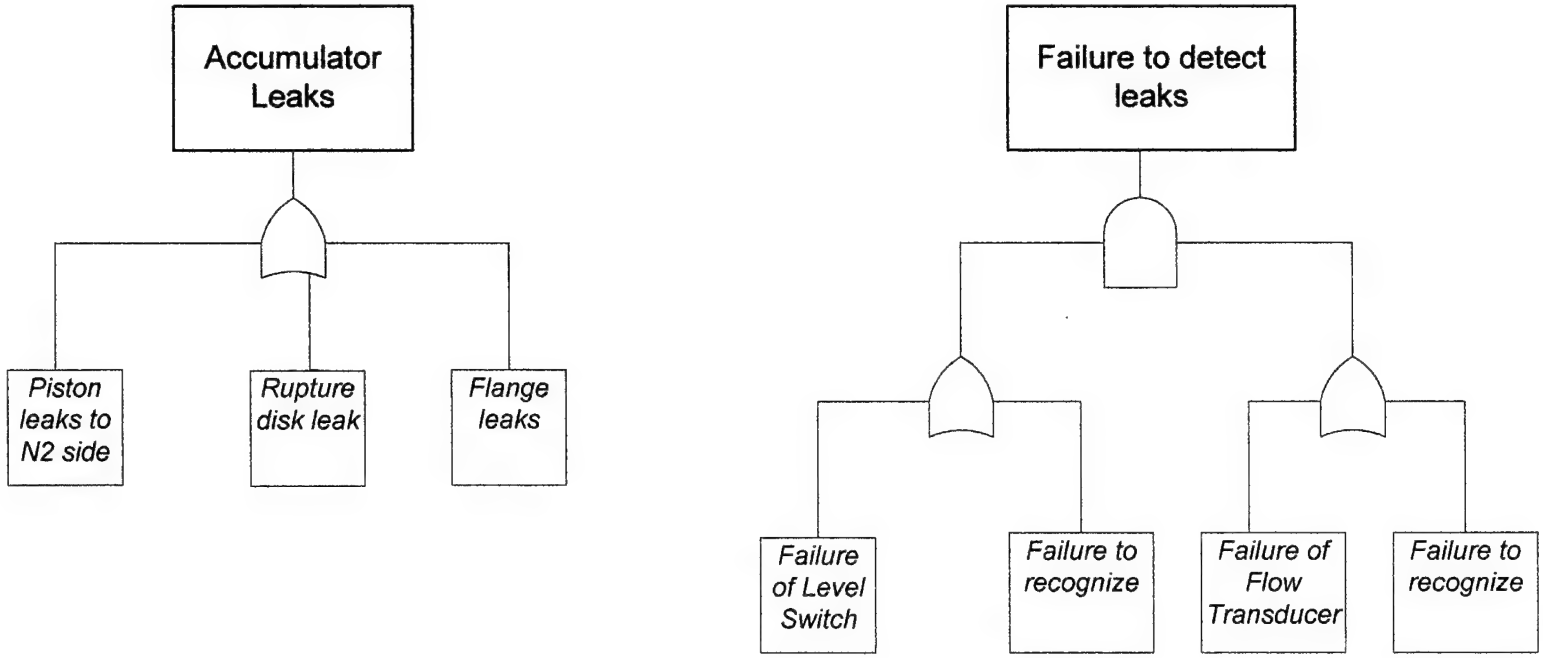

Figure A.4—Accumulator Leaks and Failure to Detect Leaks

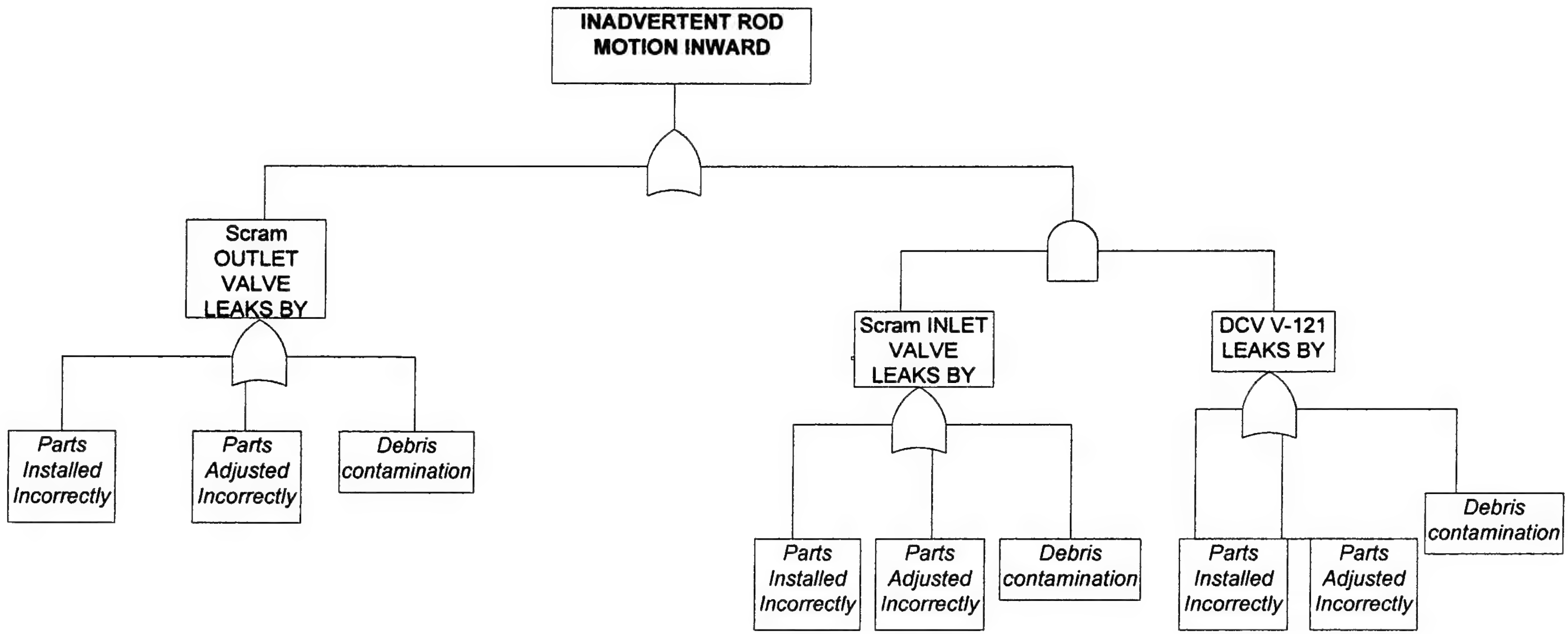

Figure A.5—Top Event 3 (Inadvertent Rod Motion Inward)

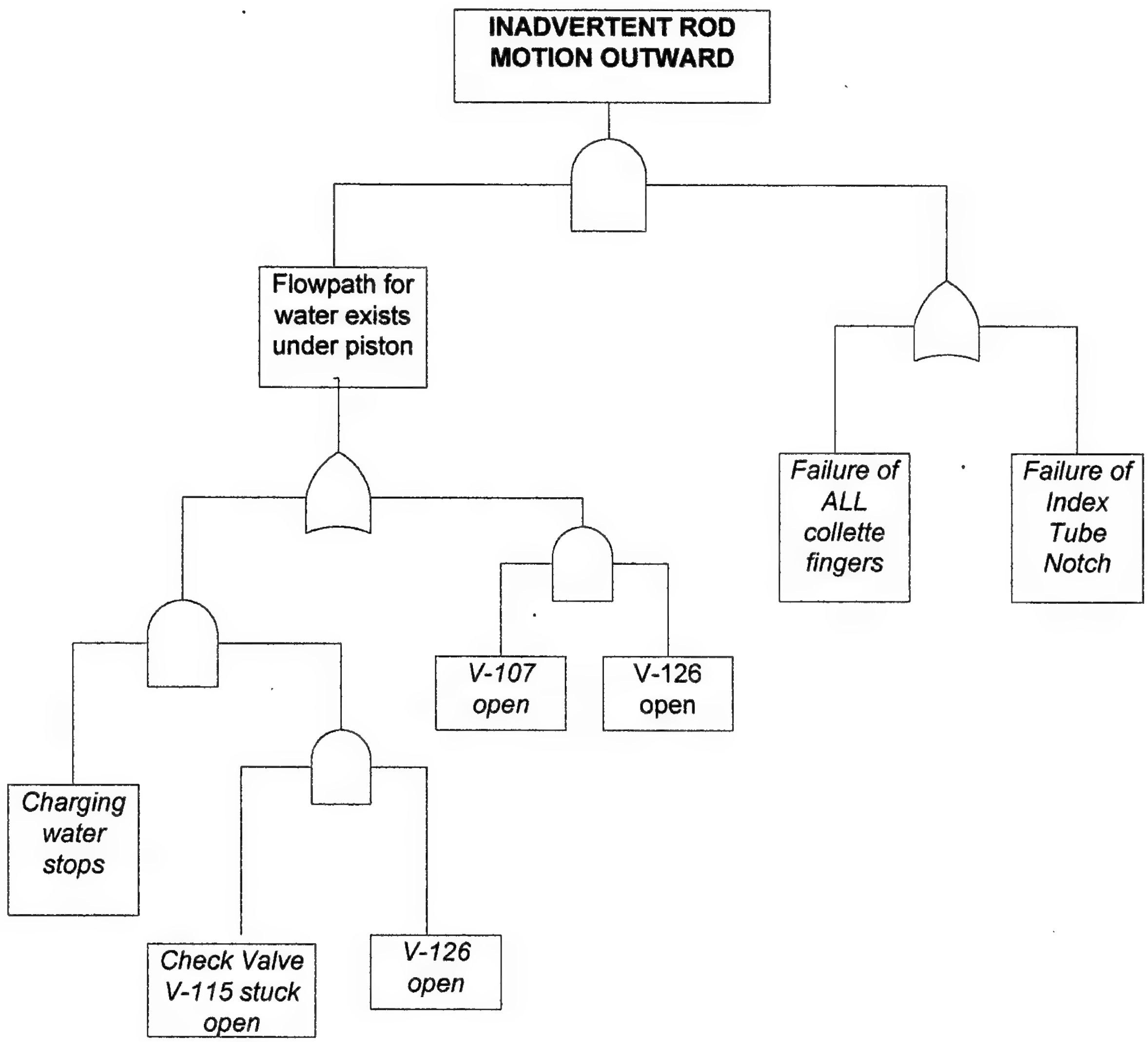

Figure A.6—Top Event 4 (Inadvertent Rod Motion Outward)

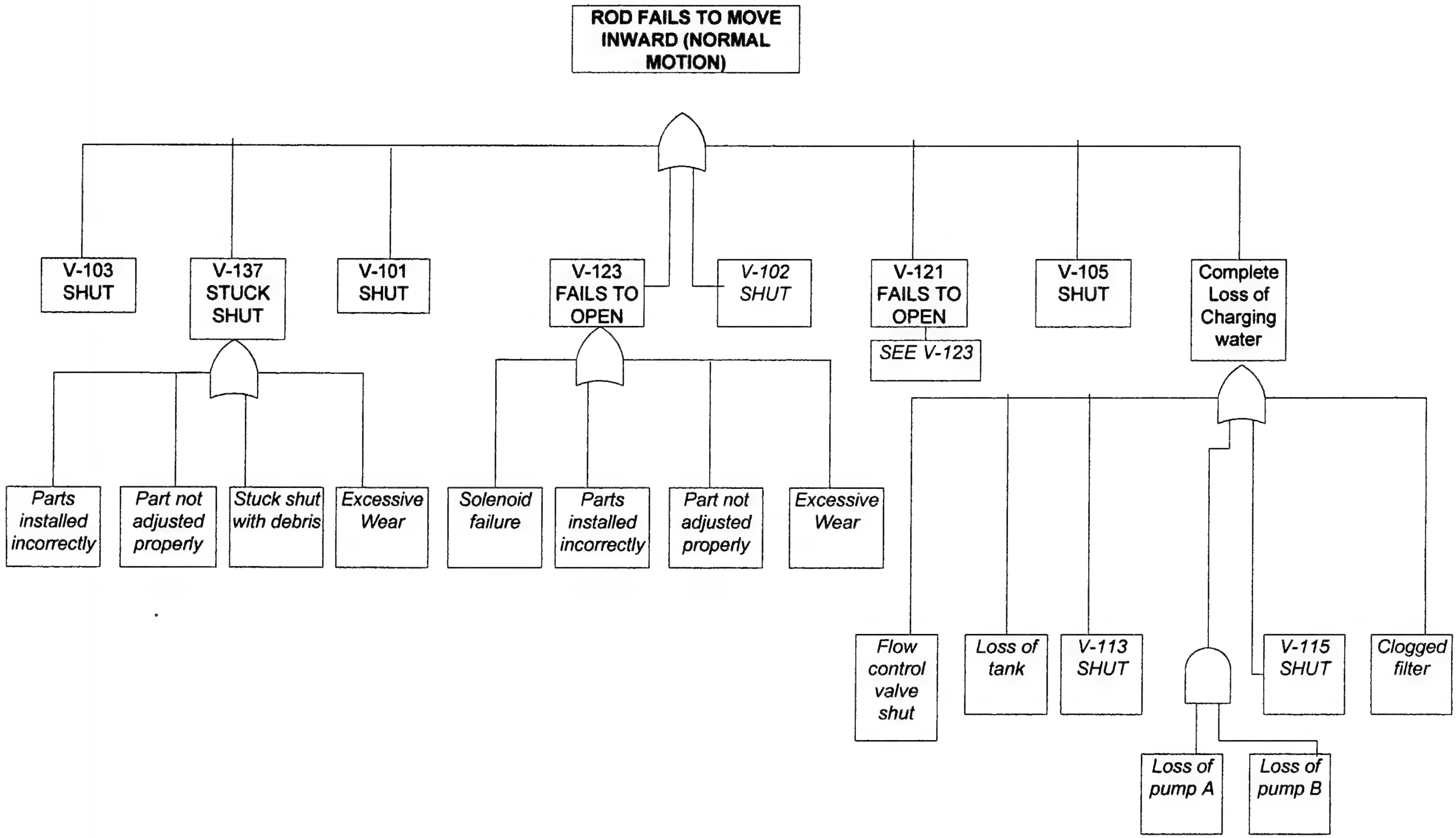

Figure A.7—Top Event 5 (Rod Fails to Move Inward)

BRUNSWICK 1

TABLE A.1

REPORT TIME: 6/10/77-3/25/96 **REPORT TIME INTERVAL (YEARS): 18.75**

BASIC EVENTS PER COMPONENT

		NUMBER OF SERVICE FAILURES		FAILURE RATES	
				BASELINE	W/STRESS
SSPV FAIL TO VENT DUE TO FOREIGN MATERIALS					
Debris Intrusion		2	2	0.0007786	0.0007786
Improper substances used during maintenance	H	2	2	0.0007786	0.0015572
SSPV FAIL TO VENT DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	7	7	0.0027251	0.0054501
Adjustment Errors	H	1	1	0.0003893	0.0007786
Excessive wear of components		5	5	0.0019465	0.0019465
Manufacturing defects		1	1	0.0003893	0.0003893
SCRAM INLET VALVE FAIL TO MOVE DUE TO FOREIGN MATERIAL					
Debris Intrusion		1	1	0.0003893	0.0003893
Improper substances used during maintenance	H	1	1	0.0003893	0.0007786
SCRAM INLET VALVE FAIL TO MOVE DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.0003893	0.0007786
Adjustment Errors	H	2	2	0.0007786	0.0015572
Excessive wear of components		14	14	0.0054501	0.0054501
Manufacturing defects		1	1	0.0003893	0.0003893
SCRAM OUTLET VALVE FAIL TO MOVE DUE TO FOREIGN MATERIAL					
Debris Intrusion		1	1	0.0003893	0.0003893

Improper substances used during maintenance	H	1	1	0.0003893	0.0007786
SCRAM OUTLET VALVE FAIL TO MOVE DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.0003893	0.0007786
Adjustment Errors	H	1	1	0.0003893	0.0007786
Excessive wear of components		1	1	0.0003893	0.0003893
Manufacturing defects		1	1	0.0003893	0.0003893
NITROGEN VOLUME LEAKAGE					
V-111 leakage		36	36	0.0140146	0.0140146
Pressure boundary failure		1	1	0.0003893	0.0003893
Leakage from flanges		1	1	0.0003893	0.0003893
Leakage from indicator connections		2	2	0.0007786	0.0007786
ACCUMULATOR LEAKAGE					
Piston leakage to Nitrogen side		15	15	0.0058394	0.0058394
Flange leakage		1	1	0.0003893	0.0003893
Rupture disk leakage		1	1	0.0003893	0.0003893
Pressure boundary failure		1	1	0.0003893	0.0003893
NITROGEN VOLUME FAILURE TO DETECT LEAKS					
Failure of operators	H			2.00E-06	0.000004
Failure of pressure switch		1	1	0.0003893	0.0003893
Failure of indicator		1	1	0.0003893	0.0003893
Failure of level switch		1	1	0.0003893	0.0003893
ACCUMULATOR VOLUME FAILURE TO DETECT LEAKS					
Failure of operators	H			2.00E-06	1.00E+00

Failure of pressure switch		1	1	0.0003893	0.0003893
Failure of indicator		1	1	0.0003893	0.0003893
Failure of level switch		1	1	0.0003893	0.0003893
CHECK VALVE FAILURE					
Debris intrusion		1	1	0.0003893	0.0003893
Parts incorrectly installed	H	1	1	0.0003893	0.0007786
Excessive wear of components		2	2	0.0007786	0.0007786
Manufacturing defects		1	1	0.0003893	0.0003893
DIRECTIONAL CONTROL VALVE FAILURE					
Solenoid/electrical component failure		6	6	0.0023358	0.0023358
Improper parts installation	H	1	1	0.0003893	0.0007786
Improper adjustment	H	1	1	0.0003893	0.0007786
Excessive wear of components		1	1	0.0003893	0.0003893
CHARGING WATER FAILURE					
Boundary failure		1	1	0.0003893	0.0003893
Failure to restore flow path	H			1.20E-05	0.000024
Loss of water supply		1	1	0.0003893	0.0003893
Loss of pump A		1	1	0.0003893	0.0003893
Loss of pump B		1	1	0.0003893	0.0003893
V-115 shut	H			2.00E-06	0.000004
V-113 shut	H			2.00E-06	0.000004
Failure of flow transducer		1	1	0.0003893	0.0003893
Clogged filter		2	2	0.0007786	0.0007786
ACCUMULATOR PISTON FAILURE		1	1	0.0003893	0.0003893
FAILURE TO RESTORE VALVES TO REQUIRED POSITIONS					
V-101	H			2.00E-06	0.000004

V-102	H			2.00E-06	0.000004
V-103	H			2.00E-06	0.000004
V-105	H			2.00E-06	0.000004
V-107	H			2.00E-06	0.000004
V-112	H			2.00E-06	0.000004
FAILURE TO RECOGNIZE	H			2.00E-06	0.000004
SCRAM DISCHARGE VOLUME					
Vent valve shut		1	1	0.0003893	0.0003893
Discharge valve shut		1	1	0.0003893	0.0003893
FAILURE OF COLLETTE FINGERS				1.00E-06	1.00E-06
FAILURES OF INDEX TUBE NOTCH				1.00E-06	1.00E-06

FAILURE FREQUENCIES		
	BASELINE	W/STRESS
TOP EVENT 1:	8.24E-03	9.89E-03
TOP EVENT 2:	3.58353E-05	5.92744E-05
TOP EVENT 3:	1.57E-03	2.35E-03
TOP EVENT 4:	1.56E-20	3.74E-20
TOP EVENT 5:	7.42E-03	9.39E-03
TOP EVENT 6:	4.29E-03	6.24E-03

PEACH BOTTOM 3

TABLE A.2

REPORT TIME: 7/22/76-11/28/93 **REPORT TIME INTERVAL (YEARS): 17.3**

BASIC EVENTS PER COMPONENT		NUMBER OF SERVICE FAILURES		FAILURE RATES BASELINE	W/STRESS
SSPV FAIL TO VENT DUE TO FOREIGN MATERIALS					
Debris Intrusion		1	1	0.000422	0.000422
Improper substances used during maintenance	H	4	4	0.001688	0.003375
SSPV FAIL TO VENT DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.000422	0.000844
Adjustment Errors	H	1	1	0.000422	0.000844
Excessive wear of components		1	1	0.000422	0.000422
Manufacturing defects		1	1	0.000422	0.000422
SCRAM INLET VALVE FAIL TO MOVE DUE TO FOREIGN MATERIAL					
Debris Intrusion		1	1	0.000422	0.000422
Improper substances used during maintenance	H	1	1	0.000422	0.000844
SCRAM INLET VALVE FAIL TO MOVE DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	3	3	0.001266	0.002532
Adjustment Errors	H	1	1	0.000422	0.000844
Excessive wear of components		6	6	0.002532	0.002532
Manufacturing defects		1	1	0.000422	0.000422
SCRAM OUTLET VALVE FAIL TO MOVE DUE TO FOREIGN MATERIAL					
Debris Intrusion		1	1	0.000422	0.000422

Improper substances used during maintenance	H	1	1	0.000422	0.000844
SCRAM OUTLET VALVE FAIL TO MOVE DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H			0.000002	0.000004
Adjustment Errors	H	1	1	0.000422	0.000844
Excessive wear of components		1	1	0.000422	0.000422
Manufacturing defects		1	1	0.000422	0.000422
NITROGEN VOLUME LEAKAGE					
V-111 leakage		126	126	0.053162	0.053162
Pressure boundary failure		1	1	0.000422	0.000422
Leakage from flanges		2	2	0.000844	0.000844
Leakage from indicator connections		3	3	0.001266	0.001266
ACCUMULATOR LEAKAGE					
Piston leakage to Nitrogen side		46	46	0.019408	0.019408
Flange leakage		1	1	0.000422	0.000422
Rupture disk leakage		1	1	0.000422	0.000422
Pressure boundary failure		1	1	0.000422	0.000422
NITROGEN VOLUME FAILURE TO DETECT LEAKS					
Failure of operators	H			2.00E-06	0.000004
Failure of pressure switch		1	1	0.000422	0.000422
Failure of indicator		1	1	0.000422	0.000422
Failure of level switch		1	1	0.000422	0.000422
ACCUMULATOR VOLUME FAILURE TO DETECT LEAKS					
Failure of operators	H			2.00E-06	1.00E+00

Failure of pressure switch		1	1	0.000422	0.000422
Failure of indicator		1	1	0.000422	0.000422
Failure of level switch		1	1	0.000422	0.000422
CHECK VALVE FAILURE					
Debris intrusion		5	5	0.00211	0.00211
Parts incorrectly installed	H			0.000002	0.000004
Excessive wear of components		5	5	0.00211	0.00211
Manufacturing defects		1	1	0.000422	0.000422
DIRECTIONAL CONTROL VALVE FAILURE					
Solenoid/electrical component failure		1	1	0.000422	0.000422
Improper parts installation	H	1	1	0.000422	0.000844
Improper adjustment	H	1	1	0.000422	0.000844
Excessive wear of components		6	6	0.002532	0.002532
CHARGING WATER FAILURE					
Boundary failure		1	1	0.000422	0.000422
Flow control valve shut	H			1.20E-05	0.000024
Loss of water supply		1	1	0.000422	0.000422
Loss of pump A		1	1	0.000422	0.000422
Loss of pump B		1	1	0.000422	0.000422
V-115 shut	H			2.00E-06	0.000004
V-113 shut	H	1	1	4.22E-04	0.000844
Failure of flow transducer		1	1	0.000422	0.000422
Clogged filter		1	1	0.000422	0.000422
ACCUMULATOR PISTON FAILURE		1	1	0.000422	0.000422
FAILURE TO RESTORE VALVES TO REQUIRED POSITIONS					
V-101	H			2.00E-06	0.000004

V-102	H			2.00E-06	0.000004
V-103	H			2.00E-06	0.000004
V-105	H			2.00E-06	0.000004
V-107	H			2.00E-06	0.000004
V-112	H			2.00E-06	0.000004
FAILURE TO RECOGNIZE	H			2.00E-06	0.000004
SCRAM DISCHARGE VOLUME					
Vent valve shut		1	1	0.000422	0.000422
Discharge valve shut		1	1	0.000422	0.000422
FAILURE OF COLLETTE FINGERS				1.00E-06	1.00E-06
FAILURES OF INDEX TUBE NOTCH				1.00E-06	1.00E-06

FAILURE FREQUENCIES	BASELINE	STRESS
TOP EVENT 1:	5.94E-03	8.14E-03
TOP EVENT 2:	4.03E-05	6.25E-05
TOP EVENT 3:	1.28E-03	1.72E-03
TOP EVENT 4:	1.10E-20	3.04E-20
TOP EVENT 5:	1.39E-02	1.61E-02
TOP EVENT 6:	1.14E-02	1.31E-02

QUAD CITIES 1

TABLE A.3

REPORT TIME: 10/5/73-4/9/96 **REPORT TIME INTERVAL (YEARS):** **22.5**

BASIC EVENTS PER COMPONENT

		NUMBER OF SERVICE FAILURES		FAILURE RATES	
				BASELINE	W/STRESS
SSPV FAIL TO VENT DUE TO FOREIGN MATERIALS					
Debris Intrusion		1	1	0.000324	0.000324
Improper substances used during maintenance	H	1	1	0.000324	0.000649
SSPV FAIL TO VENT DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.000324	0.000649
Adjustment Errors	H	1	1	0.000324	0.000649
Excessive wear of components		20	20	0.006488	0.006488
Manufacturing defects		1	1	0.000324	0.000324
SCRAM INLET VALVE FAIL TO MOVE DUE TO FOREIGN MATERIAL					
Debris Intrusion		1	1	0.000324	0.000324
Improper substances used during maintenance	H	1	1	0.000324	0.000649
SCRAM INLET VALVE FAIL TO MOVE DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.000324	0.000649
Adjustment Errors	H	18	18	0.005839	0.011679
Excessive wear of components		1	1	0.000324	0.000324
Manufacturing defects		1	1	0.000324	0.000324
SCRAM OUTLET VALVE FAIL TO MOVE DUE TO FOREIGN MATERIAL					
Debris Intrusion		1	1	0.000324	0.000324

Improper substances used during maintenance	H	1	1	0.000324	0.000649
SCRAM OUTLET VALVE FAIL TO MOVE DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.000324	0.000649
Adjustment Errors	H	31	31	0.010057	0.020114
Excessive wear of components		1	1	0.000324	0.000324
Manufacturing defects		1	1	0.000324	0.000324
NITROGEN VOLUME LEAKAGE					
V-111 leakage		44	44	0.014274	0.014274
Pressure boundary failure		1	1	0.000324	0.000324
Leakage from flanges		1	1	0.000324	0.000324
Leakage from indicator connections		64	64	0.020762	0.020762
ACCUMULATOR LEAKAGE					
Piston leakage to Nitrogen side		19	19	0.006164	0.006164
Flange leakage		1	1	0.000324	0.000324
Rupture disk leakage		1	1	0.000324	0.000324
Pressure boundary failure		1	1	0.000324	0.000324
NITROGEN VOLUME FAILURE TO DETECT LEAKS					
Failure of operators	H			2.00E-06	0.000004
Failure of pressure switch		4	4	0.001298	0.001298
Failure of indicator		1	1	0.000324	0.000324
Failure of level switch		1	1	0.000324	0.000324
ACCUMULATOR VOLUME FAILURE TO DETECT LEAKS					
Failure of operators	H			2.00E-06	1.00E+00

Failure of pressure switch		1	1	0.000324	0.000324
Failure of indicator		1	1	0.000324	0.000324
Failure of level switch		1	1	0.000324	0.000324
CHECK VALVE FAILURE					
Debris intrusion		1	1	0.000324	0.000324
Parts incorrectly installed	H	1	1	0.000324	0.000649
Excessive wear of components		3	3	0.000973	0.000973
Manufacturing defects		1	1	0.000324	0.000324
DIRECTIONAL CONTROL VALVE FAILURE					
Solenoid/electrical component failure		2	2	0.000649	0.000649
Improper parts installation	H	1	1	0.000324	0.000649
Improper adjustment	H	4	4	0.001298	0.002595
Excessive wear of components		9	9	0.00292	0.00292
CHARGING WATER FAILURE					
Boundary failure		1	1	0.000324	0.000324
Flow control valve shut	H			1.20E-05	0.000024
Loss of water supply		1	1	0.000324	0.000324
Loss of pump A		1	1	0.000324	0.000324
Loss of pump B		1	1	0.000324	0.000324
V-115 shut	H			2.00E-06	0.000004
V-113 shut	H	2	2	6.49E-04	0.001298
Failure of flow transducer		1	1	0.000324	0.000324
Clogged filter		1	1	0.000324	0.000324
ACCUMULATOR PISTON FAILURE		1	1	0.000324	0.000324
FAILURE TO RESTORE VALVES TO REQUIRED POSITIONS					
V-101	H			2.00E-06	0.000004

V-102	H			2.00E-06	0.000004
V-103	H			2.00E-06	0.000004
V-105	H			2.00E-06	0.000004
V-107	H			2.00E-06	0.000004
V-112	H			2.00E-06	0.000004
FAILURE TO RECOGNIZE	H			2.00E-06	0.000004
SCRAM DISCHARGE VOLUME					
Vent valve shut		1	1	0.000324	0.000324
Discharge valve shut		1	1	0.000324	0.000324
FAILURE OF COLLETTE FINGERS				1.00E-06	1.00E-06
FAILURES OF INDEX TUBE NOTCH				1.00E-06	1.00E-06

FAILURE FREQUENCIES	BASELINE	STRESS
TOP EVENT 1:	7.87E-03	1.44E-02
TOP EVENT 2:	0.000108	0.000357
TOP EVENT 3:	1.11E-02	2.15E-02
TOP EVENT 4:	1.49E-20	5.58E-20
TOP EVENT 5:	1.33E-02	1.76E-02
TOP EVENT 6:	1.10E-02	1.46E-02

SUSQUEHANNA 1

TABLE A.4

REPORT TIME: 7/19/83-11/25/96 **REPORT TIME INTERVAL (YEARS): 13.3**

BASIC EVENTS PER COMPONENT

		NUMBER OF SERVICE FAILURES		FAILURE RATES	
				BASELINE	W/STRESS
SSPV FAIL TO VENT DUE TO FOREIGN MATERIALS					
Debris Intrusion		1	1	0.000549	0.000549
Improper substances used during maintenance	H	184	184	0.100982	0.201965
SSPV FAIL TO VENT DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.000549	0.001098
Adjustment Errors	H	1	1	0.000549	0.001098
Excessive wear of components		1	1	0.000549	0.000549
Manufacturing defects		1	1	0.000549	0.000549
SCRAM INLET VALVE FAIL TO MOVE DUE TO FOREIGN MATERIAL					
Debris Intrusion		1	1	0.000549	0.000549
Improper substances used during maintenance	H	1	1	0.000549	0.001098
SCRAM INLET VALVE FAIL TO MOVE DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.000549	0.001098
Adjustment Errors	H	1	1	0.000549	0.001098
Excessive wear of components		30	30	0.016465	0.016465
Manufacturing defects		1	1	0.000549	0.000549
SCRAM OUTLET VALVE FAIL TO MOVE DUE TO FOREIGN MATERIAL					
Debris Intrusion		1	1	0.000549	0.000549

Improper substances used during maintenance	H	1	1	0.000549	0.001098
SCRAM OUTLET VALVE FAIL TO MOVE DUE TO MECHANICAL FAILURE					
Parts Incorrectly Installed/Improper Rebuild	H	1	1	0.000549	0.001098
Adjustment Errors	H	1	1	0.000549	0.001098
Excessive wear of components		1	1	0.000549	0.000549
Manufacturing defects		1	1	0.000549	0.000549
NITROGEN VOLUME LEAKAGE					
V-111 leakage		9	9	0.004939	0.004939
Pressure boundary failure		1	1	0.000549	0.000549
Leakage from flanges		1	1	0.000549	0.000549
Leakage from indicator connections		1	1	0.000549	0.000549
ACCUMULATOR LEAKAGE					
Piston leakage to Nitrogen side		16	16	0.008781	0.008781
Flange leakage		9	9	0.004939	0.004939
Rupture disk leakage		1	1	0.000549	0.000549
Pressure boundary failure		1	1	0.000549	0.000549
NITROGEN VOLUME FAILURE TO DETECT LEAKS					
Failure of operators	H			2.00E-06	0.000004
Failure of pressure switch		6	6	0.003293	0.003293
Failure of indicator		1	1	0.000549	0.000549
Failure of level switch		1	1	0.000549	0.000549
ACCUMULATOR VOLUME FAILURE TO DETECT LEAKS					
Failure of operators	H			2.00E-06	1.00E+00

Failure of pressure switch		1	1	0.000549	0.000549
Failure of indicator		1	1	0.000549	0.000549
Failure of level switch		1	1	0.000549	0.000549
CHECK VALVE FAILURE					
Debris intrusion		1	1	0.000549	0.000549
Parts incorrectly installed	H	1	1	0.000549	0.001098
Excessive wear of components		26	26	0.014269	0.014269
Manufacturing defects		1	1	0.000549	0.000549
DIRECTIONAL CONTROL VALVE FAILURE					
Solenoid/electrical component failure		1	1	0.000549	0.000549
Improper parts installation	H	1	1	0.000549	0.001098
Improper adjustment	H	1	1	0.000549	0.001098
Excessive wear of components		1	1	0.000549	0.000549
CHARGING WATER FAILURE					
Boundary Failure		1	1	0.000549	0.000549
Flow control valve shut	H			1.20E-05	0.000024
Loss of water supply		1	1	0.000549	0.000549
Loss of pump A		1	1	0.000549	0.000549
Loss of pump B		1	1	0.000549	0.000549
V-115 shut	H			2.00E-06	0.000004
V-113 shut	H			2.00E-06	0.000004
Failure of flow transducer		1	1	0.000549	0.000549
Clogged filter		1	1	0.000549	0.000549
ACCUMULATOR PISTON FAILURE		1	1	0.000549	0.000549
FAILURE TO RESTORE VALVES TO REQUIRED POSITIONS					
V-101	H			2.00E-06	0.000004

V-102	H			2.00E-06	0.000004
V-103	H			2.00E-06	0.000004
V-105	H			2.00E-06	0.000004
V-107	H			2.00E-06	0.000004
V-112	H			2.00E-06	0.000004
FAILURE TO RECOGNIZE	H			2.00E-06	0.000004
SCRAM DISCHARGE VOLUME					
Vent valve shut		1	1	0.000549	0.000549
Discharge valve shut		1	1	0.000549	0.000549
FAILURE OF COLLETTE FINGERS				1.00E-06	1.00E-06
FAILURES OF INDEX TUBE NOTCH				1.00E-06	1.00E-06

FAILURE FREQUENCIES		
	BASELINE	**STRESS**
TOP EVENT 1:	3.22E-02	6.72E-02
TOP EVENT 2:	0.001017	0.00451
TOP EVENT 3:	2.23E-03	3.35E-03
TOP EVENT 4:	3.84E-20	8.34E-20
TOP EVENT 5:	2.20E-02	2.47E-02
TOP EVENT 6:	1.92E-02	2.20E-02